

Self-Adjusting Networks

Stefan Schmid

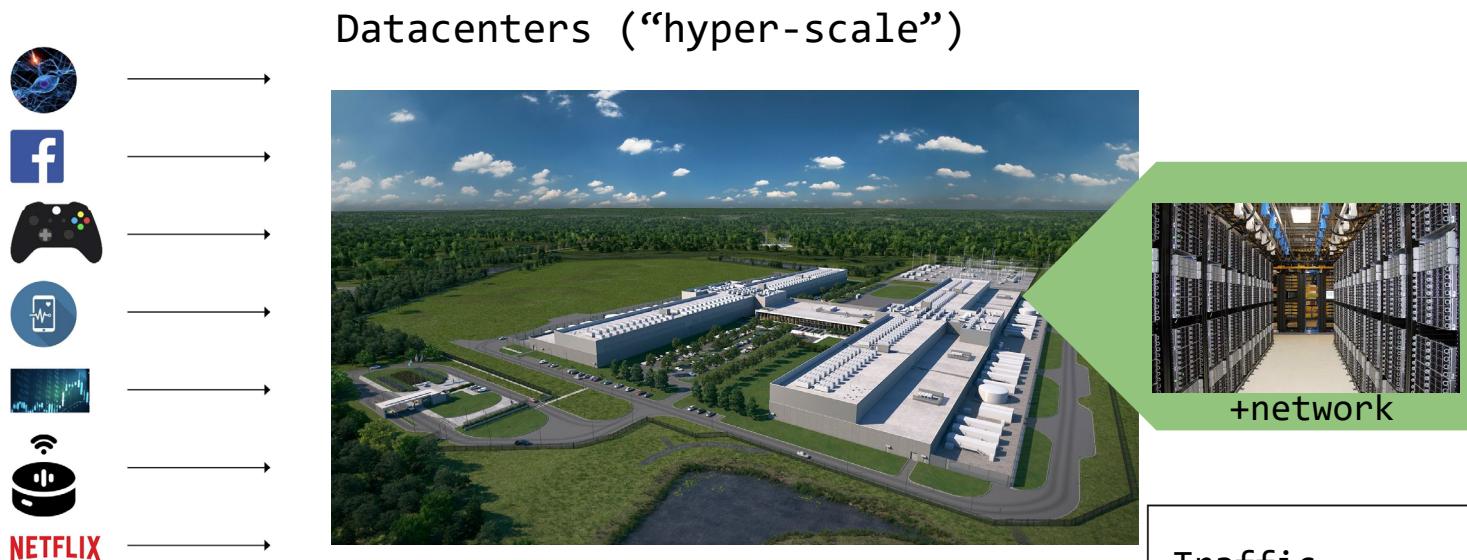
“We cannot direct the wind,
but we can adjust the sails.”

(Folklore)

Acknowledgements:

Trend

Data-Centric Applications



Interconnecting networks:
a **critical infrastructure**
of our digital society.

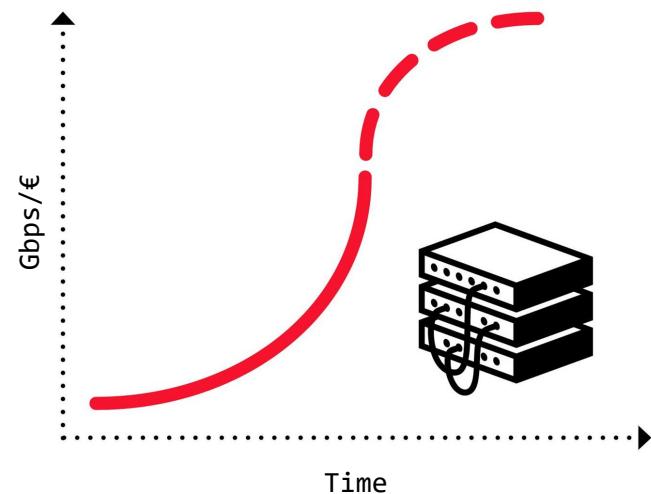
Traffic
Growth

Source: Facebook

The Problem

Huge Infrastructure, Inefficient Use

- Network equipment reaching capacity limits
 - Transistor density rates stalling
 - “End of **Moore’s Law** in networking” [1]
- Hence: more equipment, larger networks
- Resource intensive and: **inefficient**



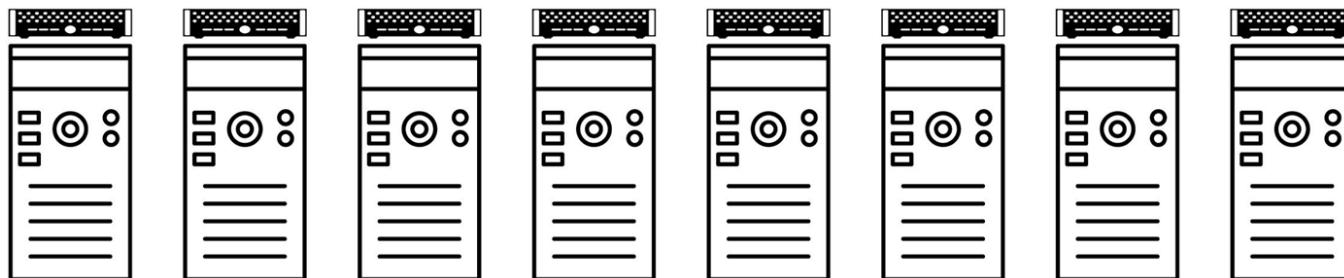
[1] Source: Microsoft, 2019

Annoying for companies,
opportunity for researchers

Root Cause

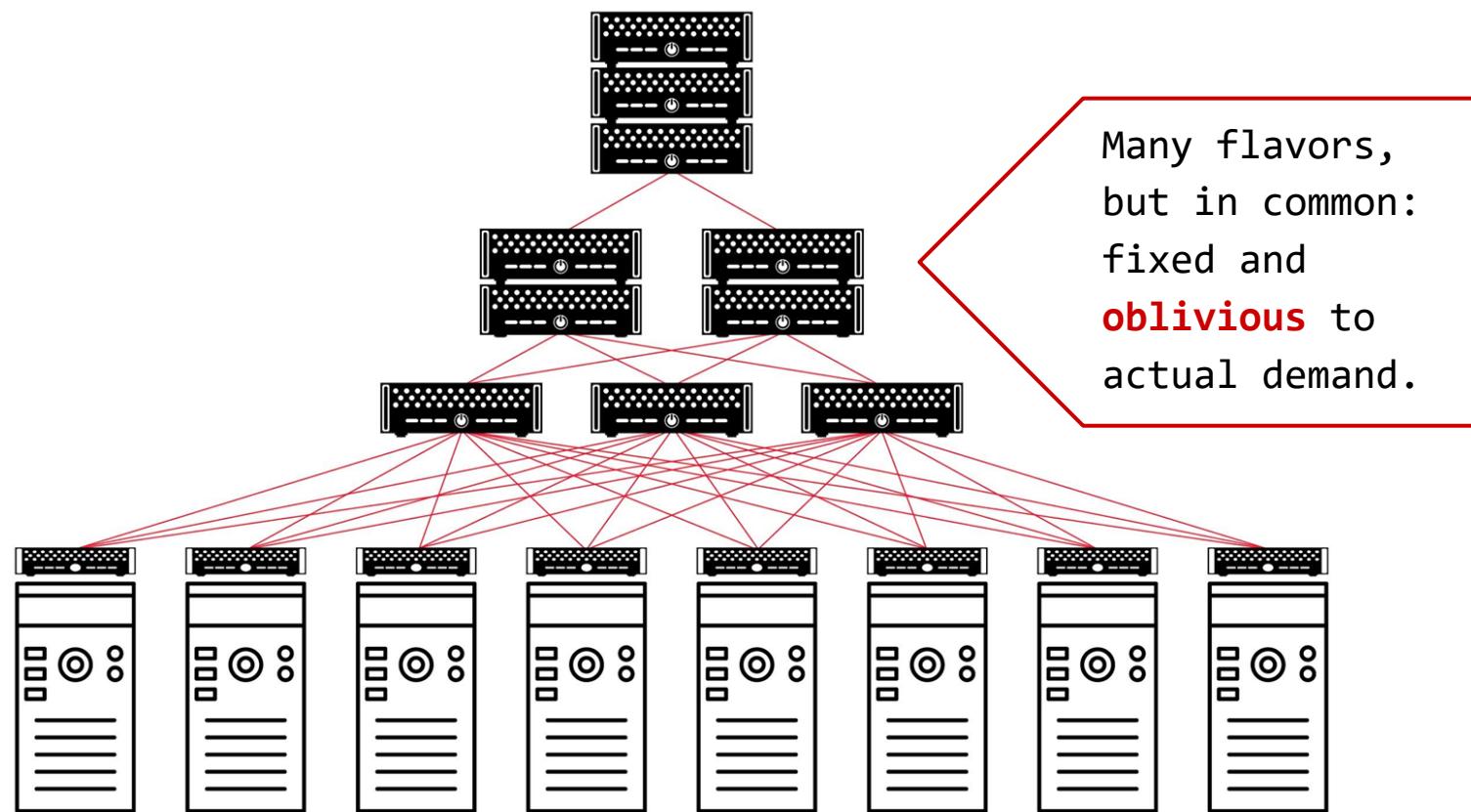
Fixed and Demand-Oblivious Topology

How to interconnect?



Root Cause

Fixed and Demand-Oblivious Topology

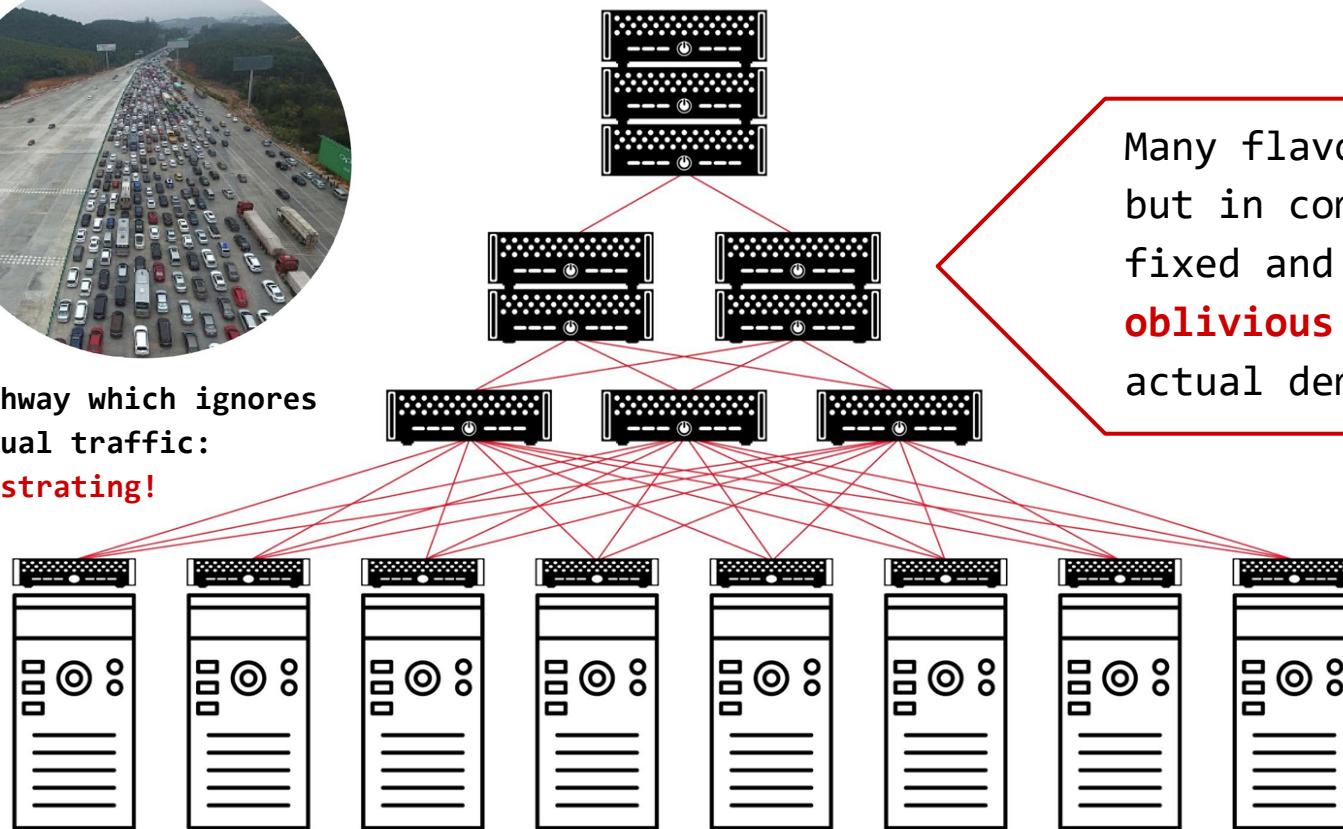


Root Cause

Fixed and Demand-Oblivious Topology



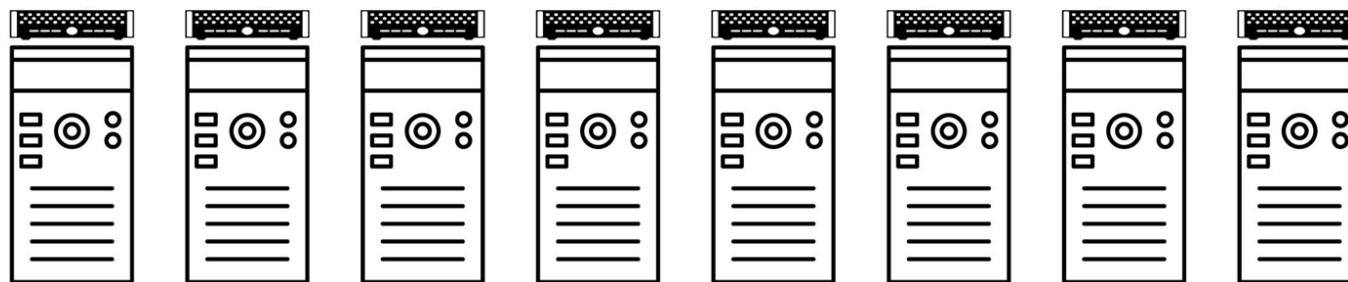
Highway which ignores
actual traffic:
frustrating!



Many flavors,
but in common:
fixed and
oblivious to
actual demand.

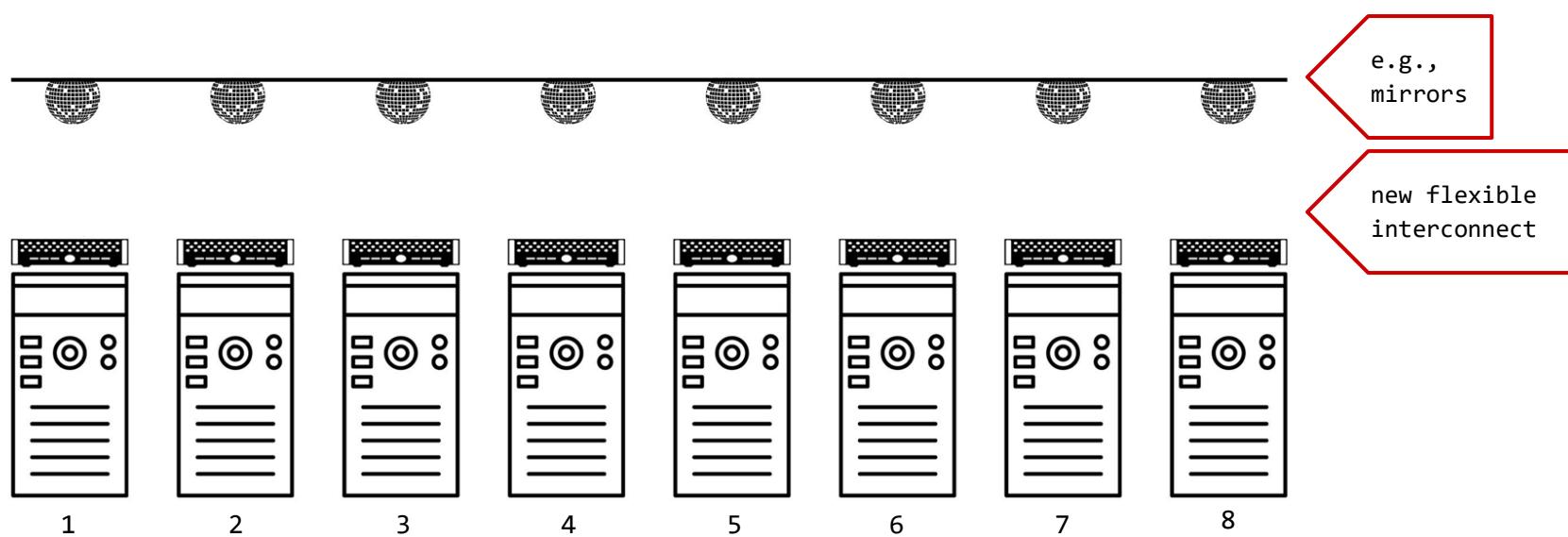
Our Vision

Flexible and Demand-Aware Topologies



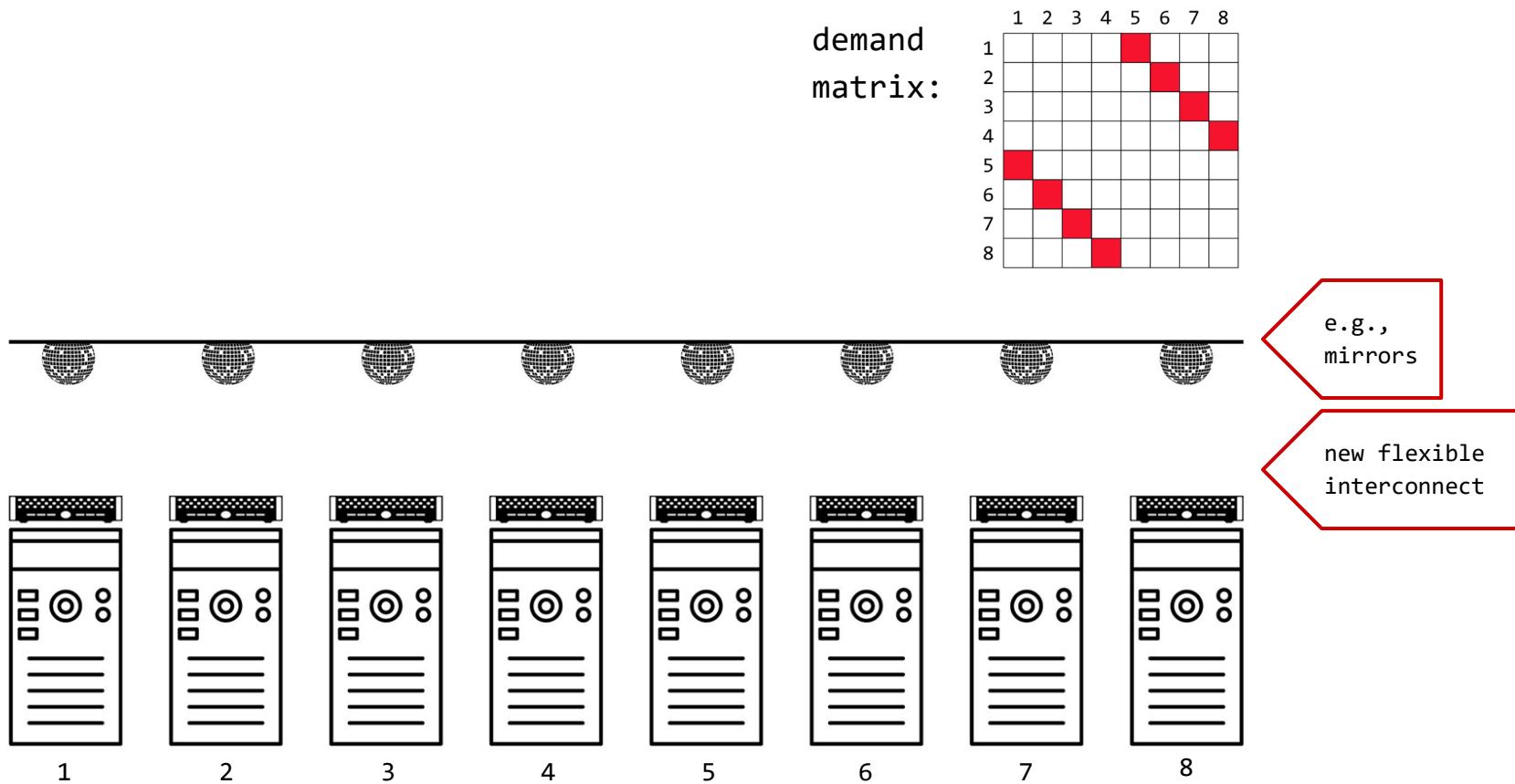
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Flexible and Demand-Aware Topologies



Our Vision

Flexible and Demand-Aware Topologies



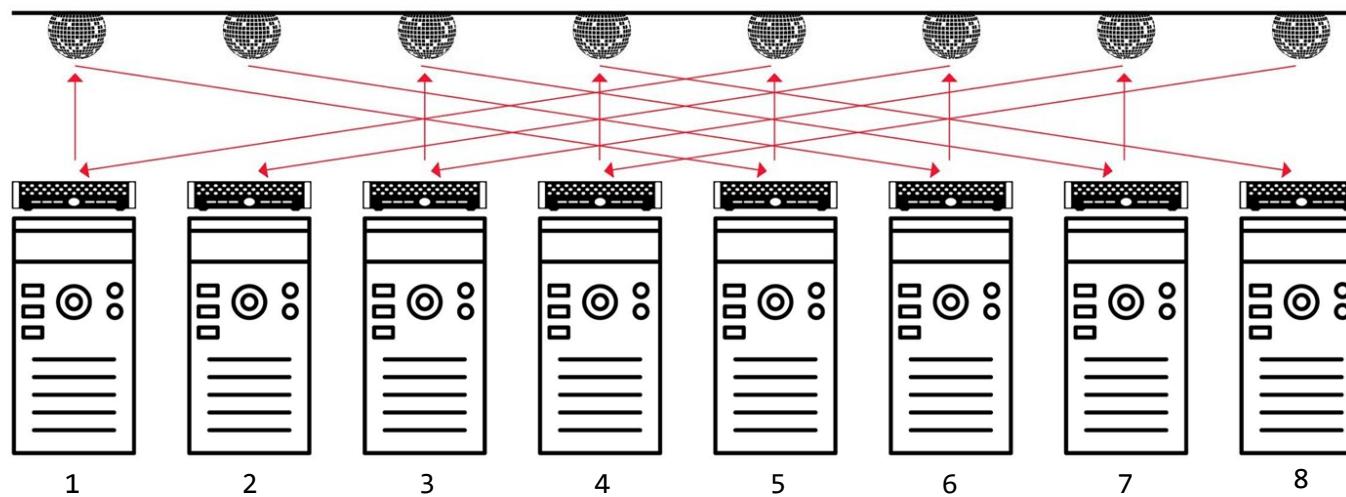
Our Vision

Flexible and Demand-Aware Topologies

Matches demand

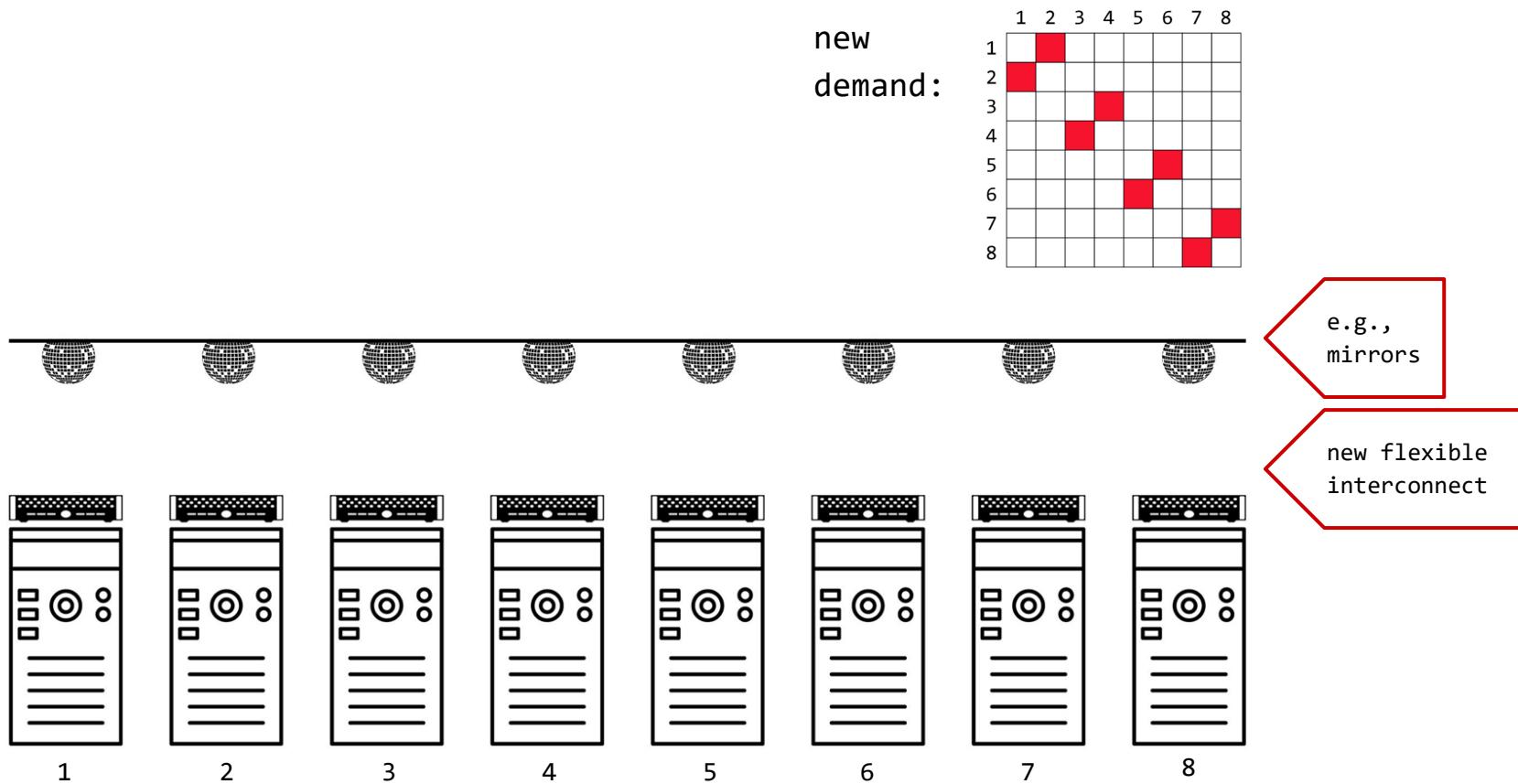
demand
matrix:

1	2	3	4	5	6	7	8
1					1		
2					1	1	
3						1	
4							1
5	1						
6		1					
7			1				
8				1			



Our Vision

Flexible and Demand-Aware Topologies

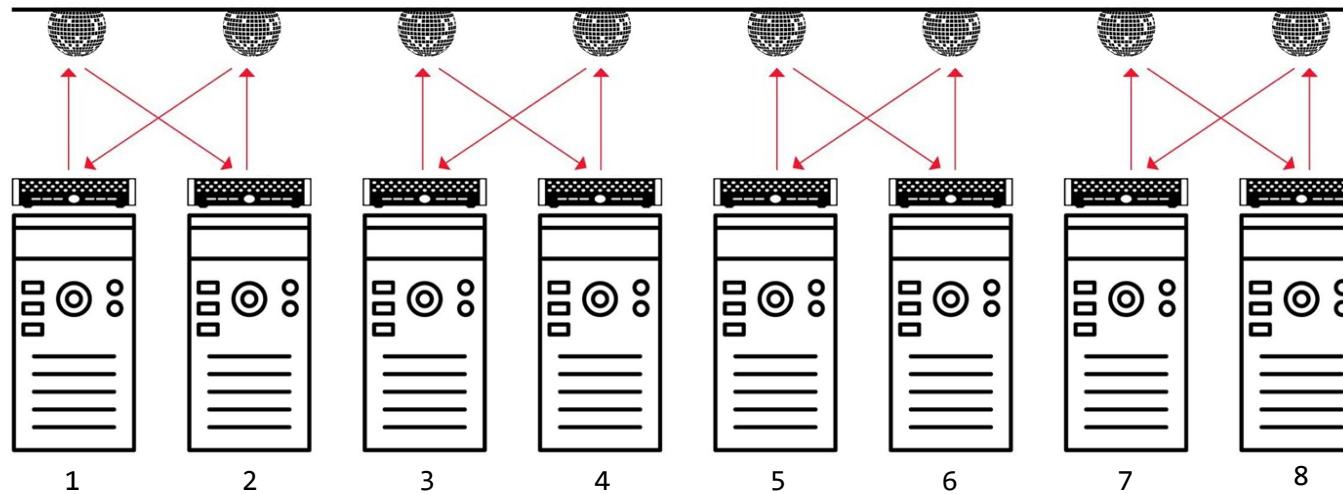
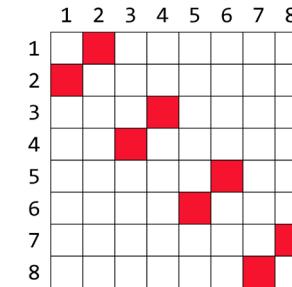


Our Vision

Flexible and Demand-Aware Topologies

Matches demand

new
demand:



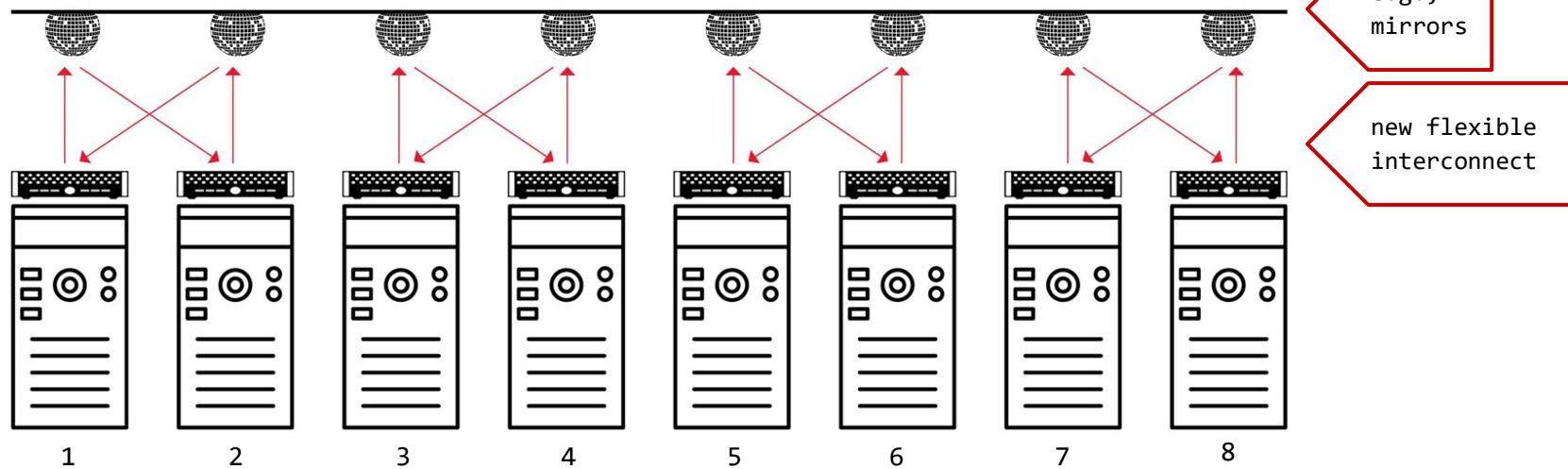
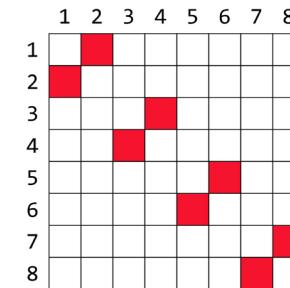
Our Vision

Flexible and Demand-Aware Topologies



Self-Adjusting
Networks

new
demand:

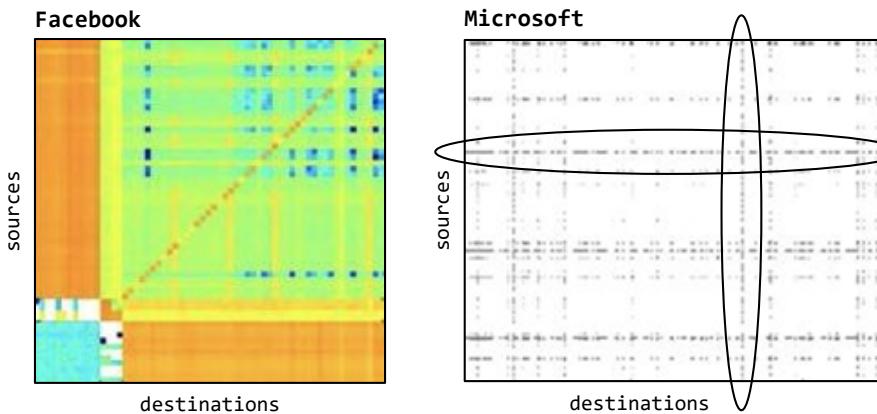


Our Motivation

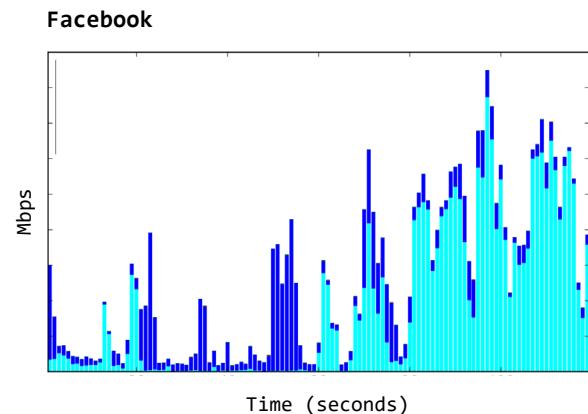
Much Structure in the Demand

Empirical studies:

traffic matrices **sparse** and **skewed**

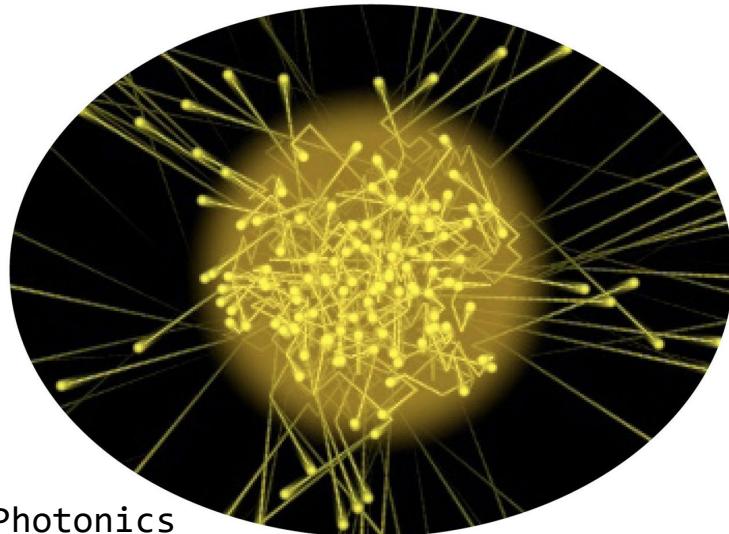


traffic **bursty** over time



My **hypothesis**: can be exploited.

Sounds Crazy? Emerging Enabling Technology.



H2020:

**“Photronics one of only five
key enabling technologies
for future prosperity.”**

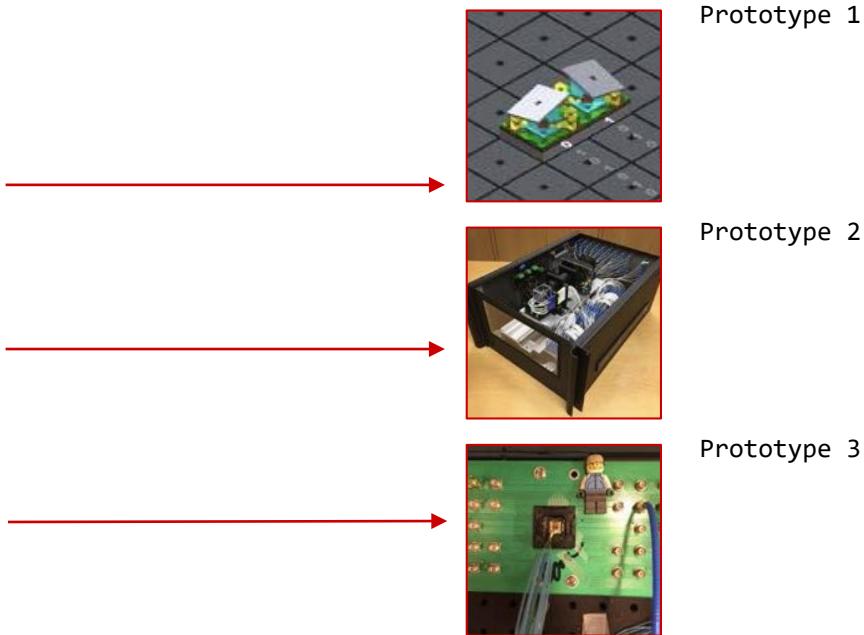
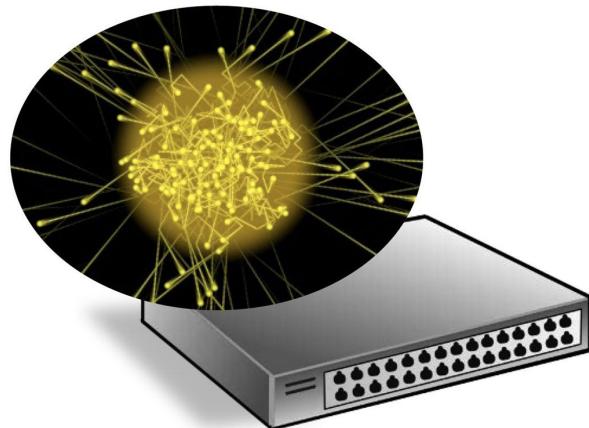
US National Research Council:
**“Photons are the new
Electrons.”**

Enabler

Novel Reconfigurable Optical Switches

→ **Spectrum** of prototypes

- Different sizes, different reconfiguration times
- From our last year's ACM **SIGCOMM** workshop



Prototype 1

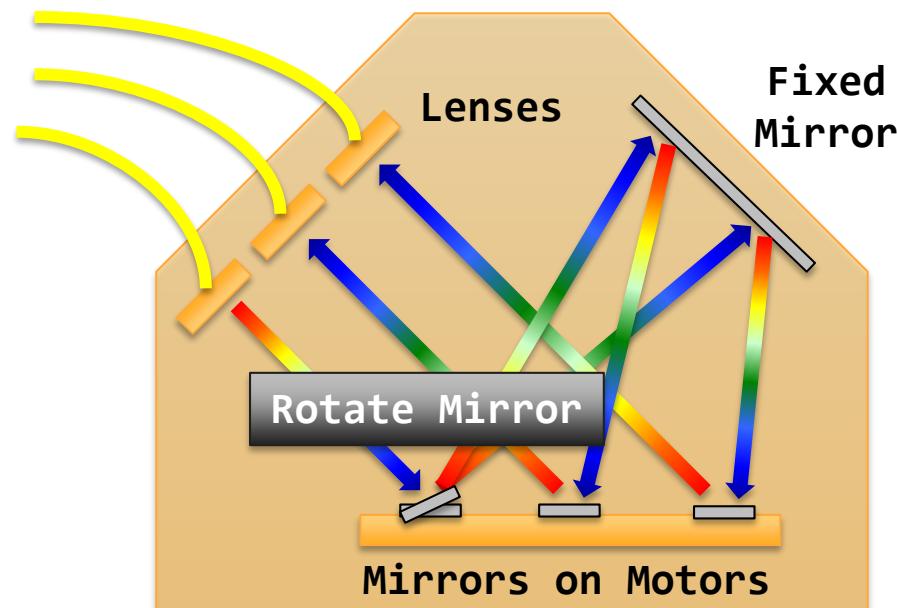
Prototype 2

Prototype 3

Example

Optical Circuit Switch

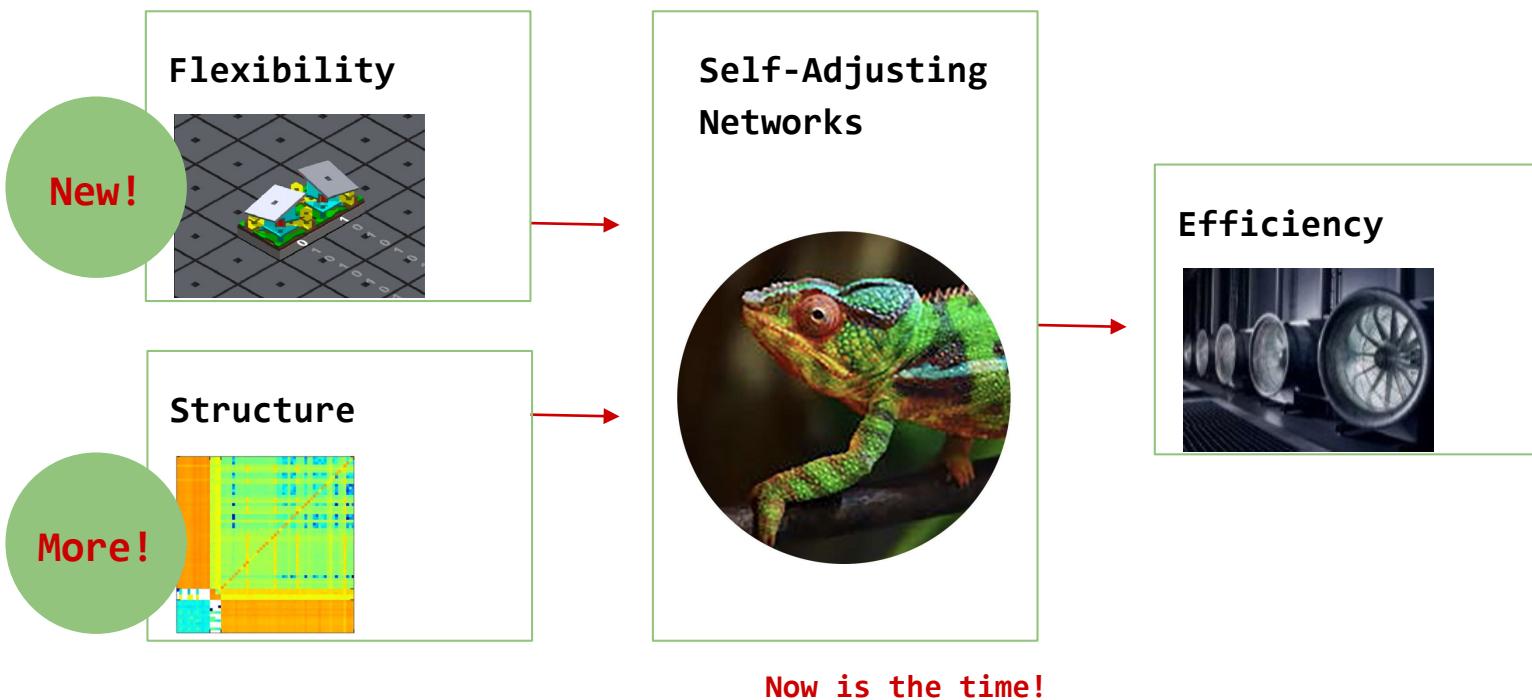
- Optical Circuit Switch rapid adaption of physical layer
 - based on rotating mirrors



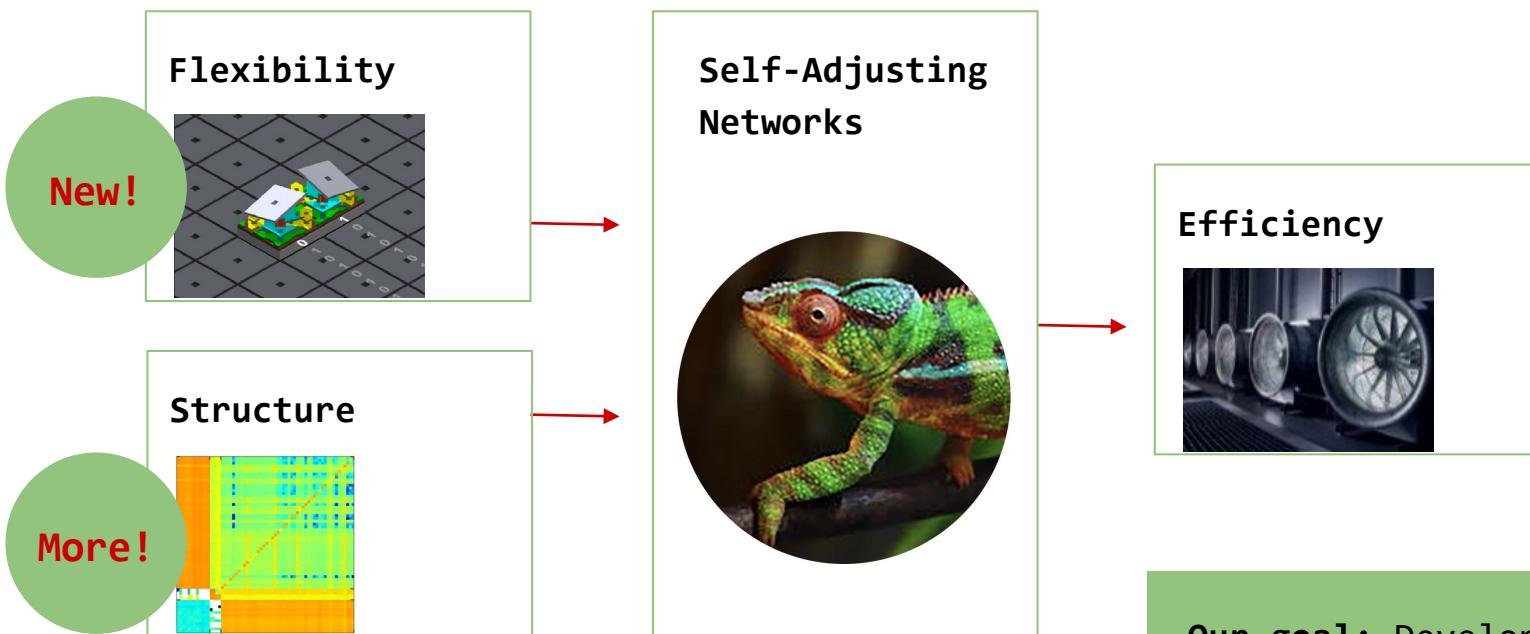
Optical Circuit Switch

By Nathan Farrington, SIGCOMM 2010

The Big Picture



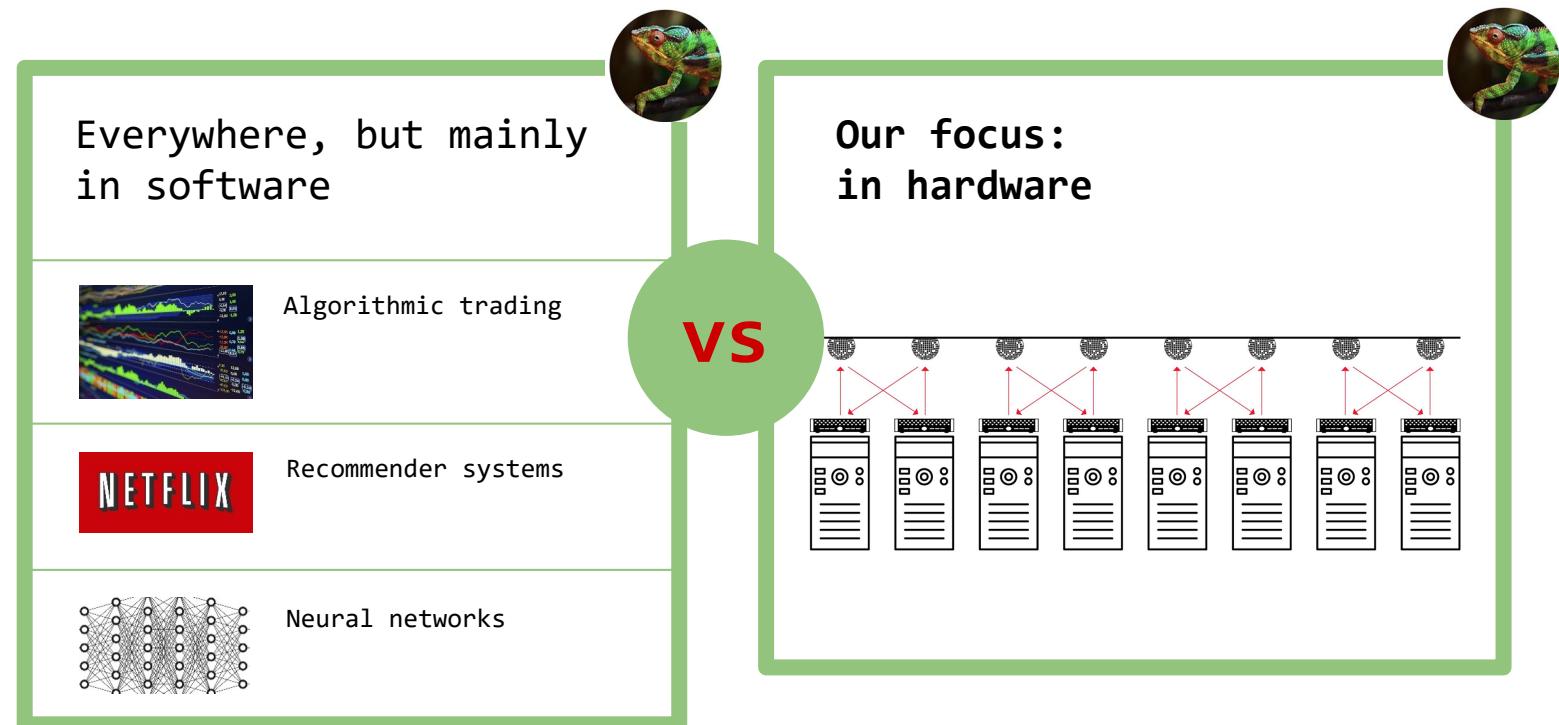
The Big Picture



Our goal: Develop the theoretical **foundations** of demand-aware, self-adjusting networks.

Unique Position

Demand-Aware, Self-Adjusting Systems



Question 1:

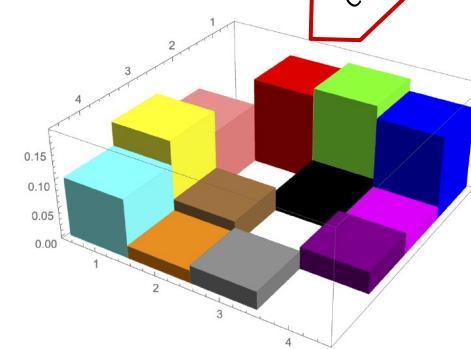
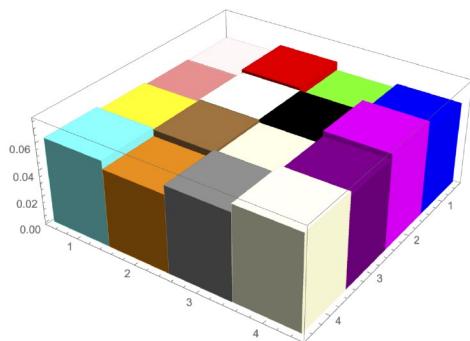
How to Quantify
such “Structure”
in the Demand?

Intuition

Which demand has more structure?

→ Traffic matrices of two different distributed ML applications

→ GPU-to-GPU



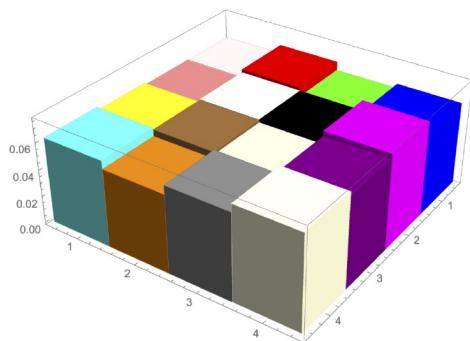
Color = communication pair

Intuition

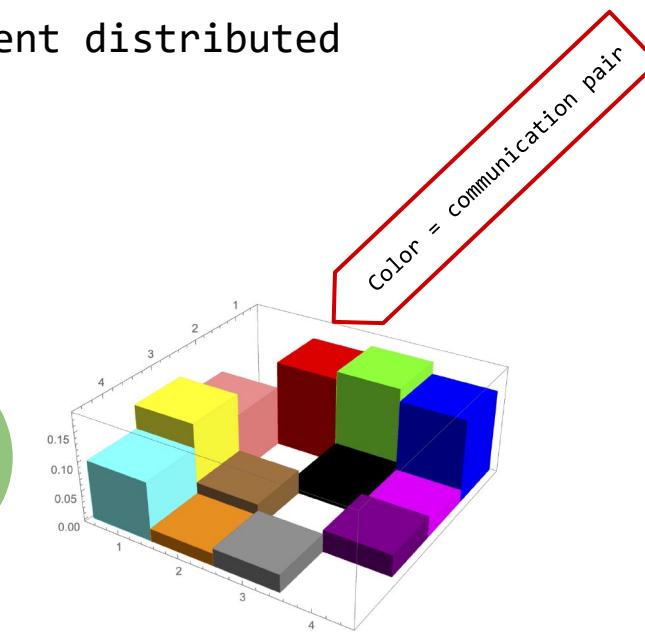
Which demand has more structure?

→ Traffic matrices of two different distributed
ML applications

→ GPU-to-GPU



More uniform

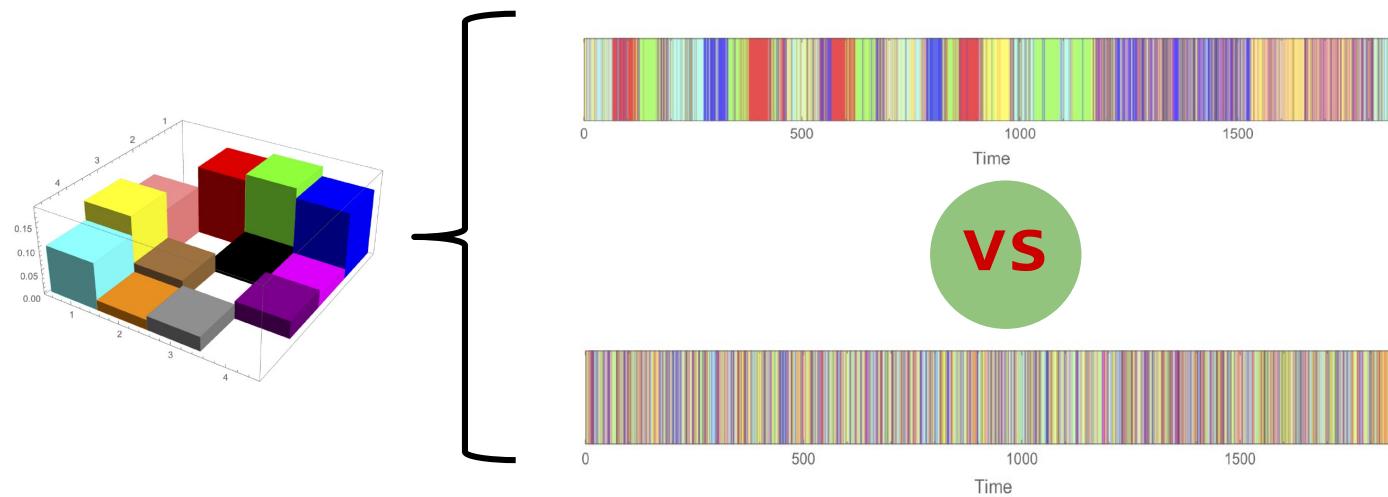


More structure

Intuition

Spatial vs temporal structure

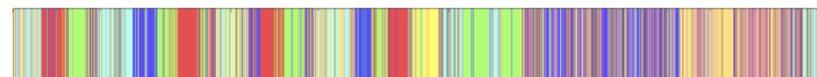
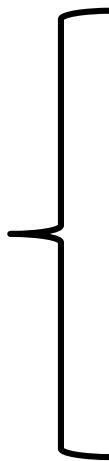
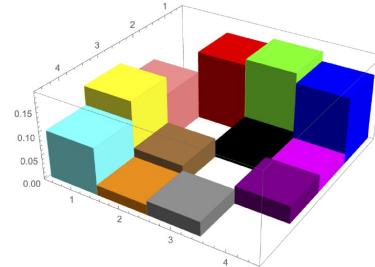
- Two different ways to generate same traffic matrix:
 - same non-temporal structure
- Which one has more structure?



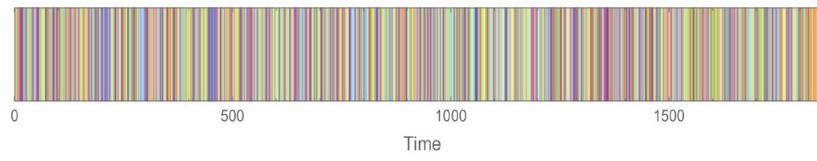
Intuition

Spatial vs temporal structure

- Two different ways to generate same traffic matrix:
 - same non-temporal structure
- Which one has more structure?



VS

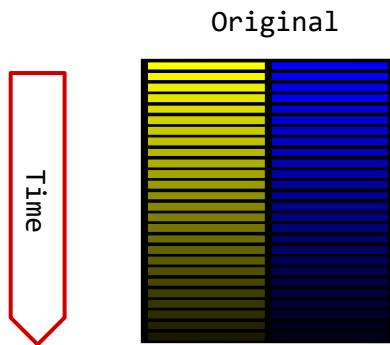


Systematically?

Trace Complexity

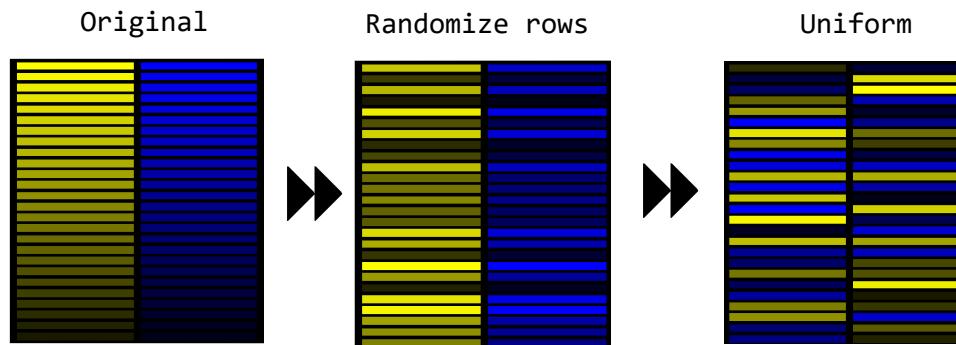
Information-Theoretic Approach

“Shuffle&Compress”



Trace Complexity

Information-Theoretic Approach
“Shuffle&Compress”

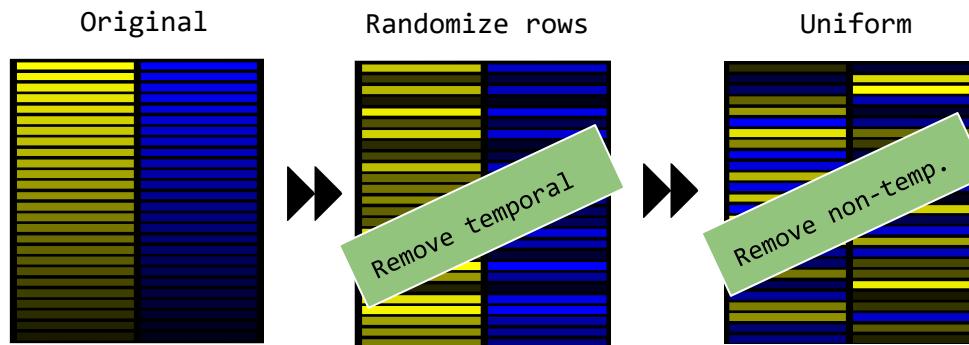


Increasing complexity (systematically randomized)

More structure (compresses better)

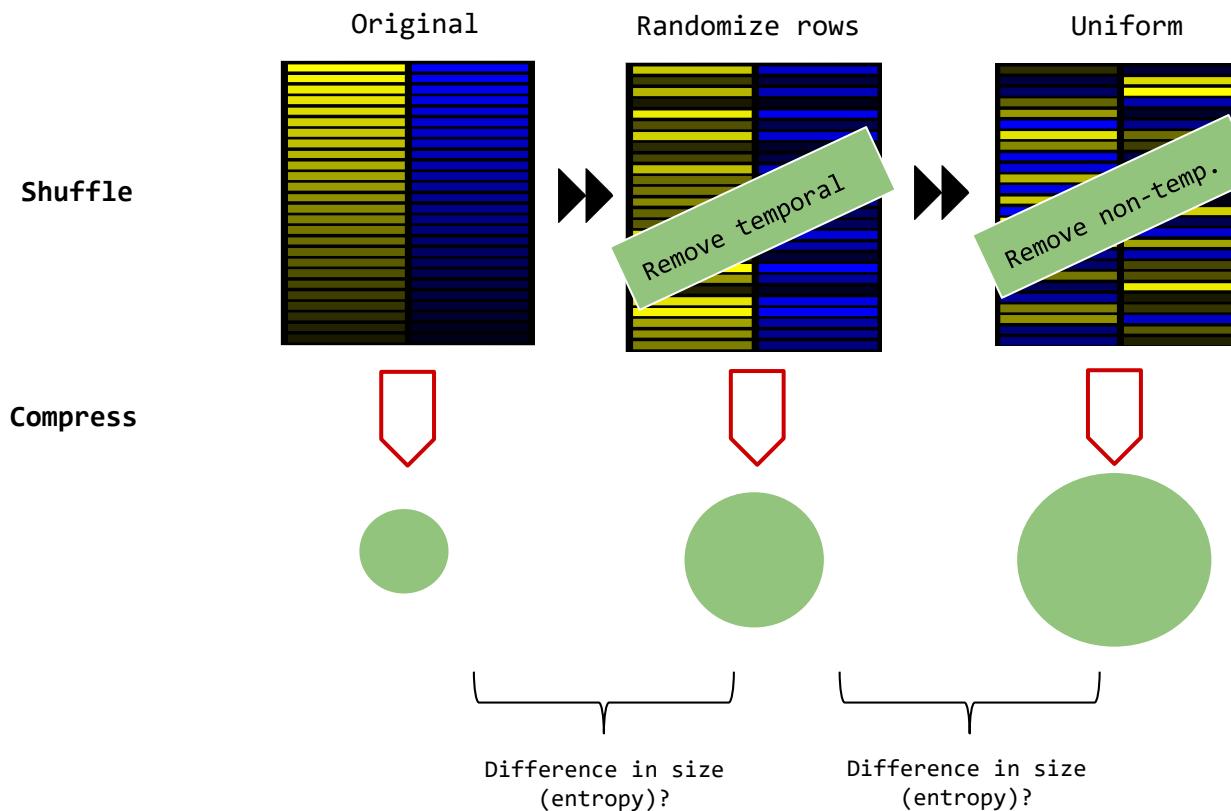
Trace Complexity

Information-Theoretic Approach
“Shuffle&Compress”



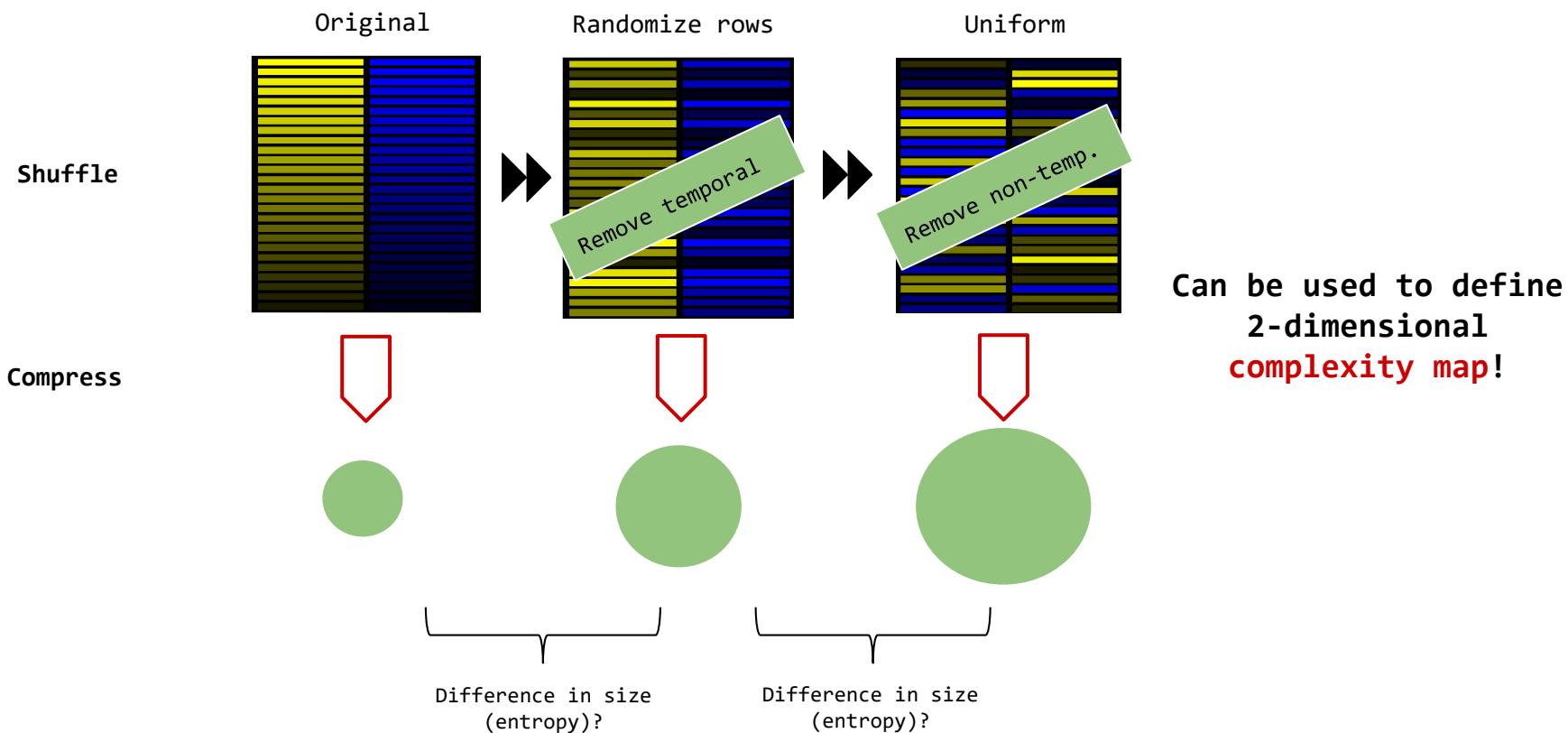
Trace Complexity

Information-Theoretic Approach
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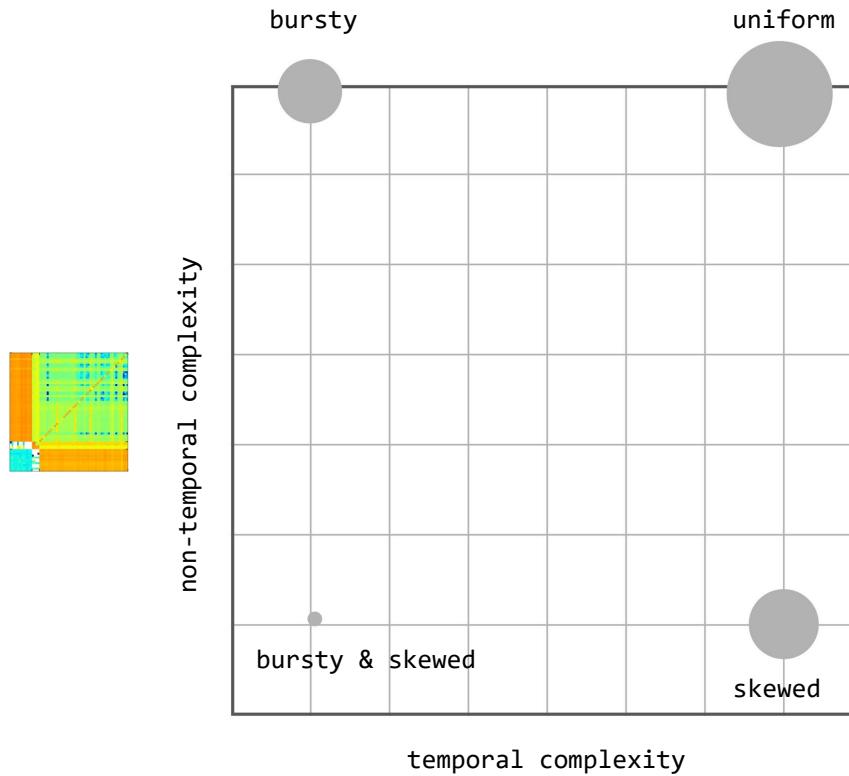
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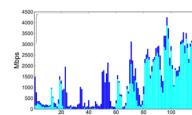
Our Methodology

Complexity Map



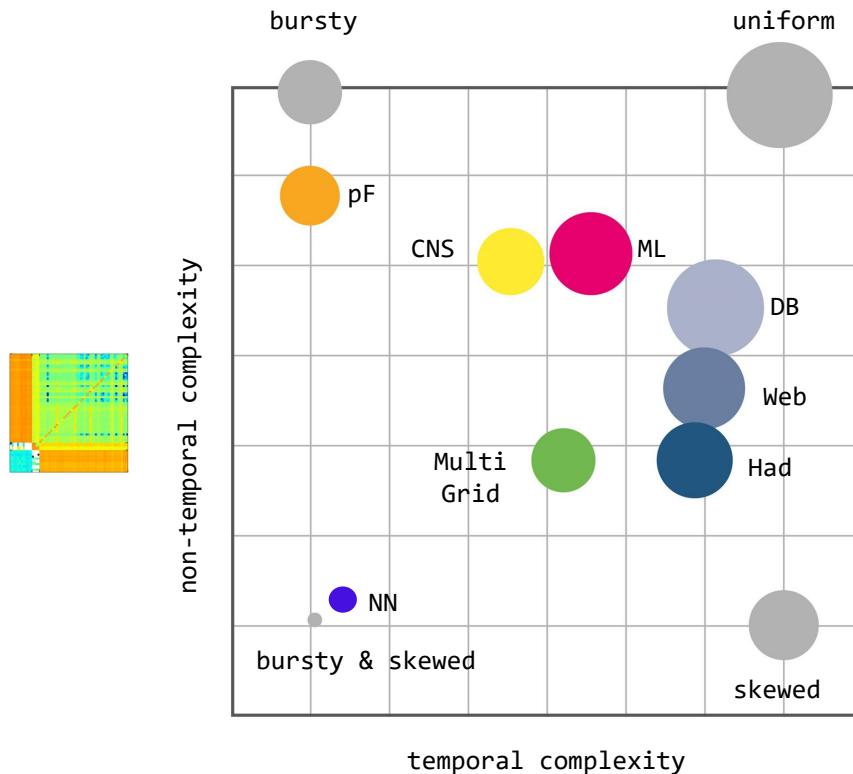
No structure

Our approach: iterative
randomization and
compression of trace to
identify dimensions of
structure.



Our Methodology

Complexity Map



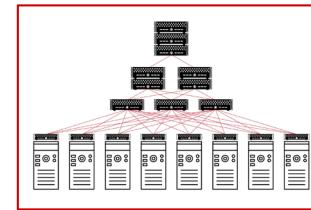
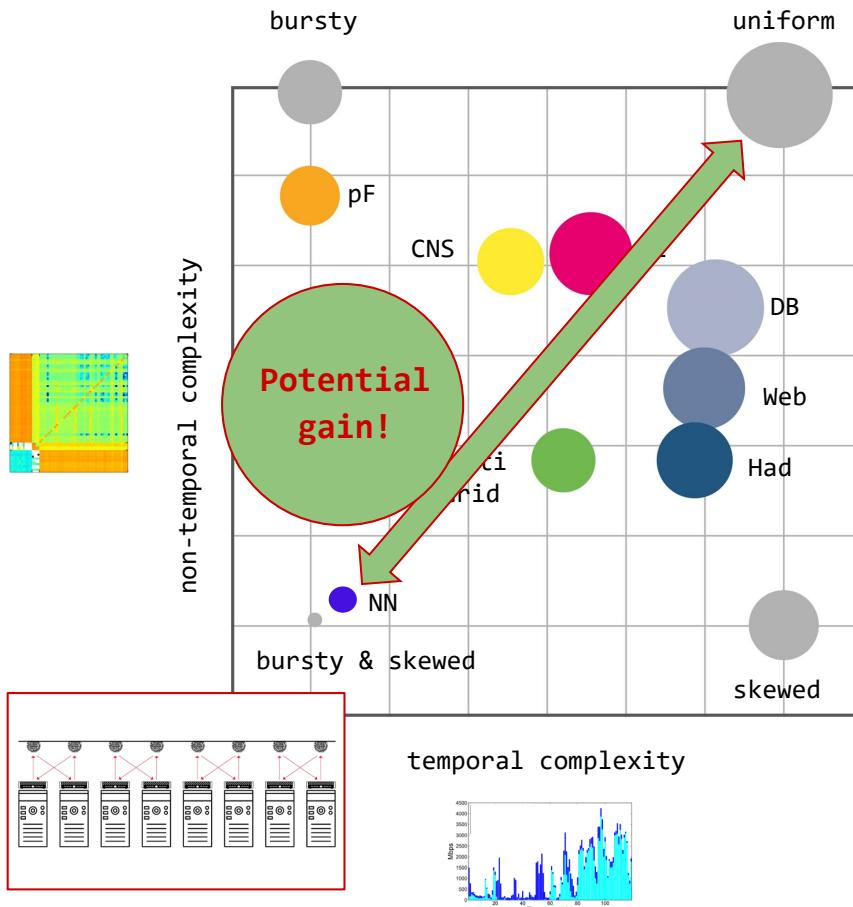
No structure

Our approach: iterative randomization and compression of trace to identify dimensions of structure.

Different structures!

Our Methodology

Complexity Map



Our approach: iterative randomization and compression of trace to identify dimensions of structure.

Different structures!

Further Reading

ACM SIGMETRICS 2020

On the Complexity of Traffic Traces and Implications

CHEN AVIN, School of Electrical and Computer Engineering, Ben Gurion University of the Negev, Israel

MANYA GHOBADI, Computer Science and Artificial Intelligence Laboratory, MIT, USA

CHEN GRINER, School of Electrical and Computer Engineering, Ben Gurion University of the Negev, Israel

STEFAN SCHMID, Faculty of Computer Science, University of Vienna, Austria

This paper presents a systematic approach to identify and quantify the types of structures featured by packet traces in communication networks. Our approach leverages an information-theoretic methodology, based on iterative randomization and compression of the packet trace, which allows us to systematically remove and measure dimensions of structure in the trace. In particular, we introduce the notion of *trace complexity* which approximates the entropy rate of a packet trace. Considering several real-world traces, we show that trace complexity can provide unique insights into the characteristics of various applications. Based on our approach, we also propose a traffic generator model able to produce a synthetic trace that matches the complexity levels of its corresponding real-world trace. Using a case study in the context of datacenters, we show that insights into the structure of packet traces can lead to improved demand-aware network designs: datacenter topologies that are optimized for specific traffic patterns.

CCS Concepts: • Networks → Network performance evaluation; Network algorithms; Data center networks; • Mathematics of computing → Information theory;

Additional Key Words and Phrases: trace complexity, self-adjusting networks, entropy rate, compress, complexity map, data centers

ACM Reference Format:

Chen Avin, Manya Ghobadi, Chen Griner, and Stefan Schmid. 2020. On the Complexity of Traffic Traces and Implications. *Proc. ACM Meas. Anal. Comput. Syst.* 4, 1, Article 20 (March 2020), 29 pages. <https://doi.org/10.1145/3379486>

1 INTRODUCTION

Packet traces collected from networking applications, such as datacenter traffic, have been shown to feature much *structure*: datacenter traffic matrices are sparse and skewed [16, 39], exhibit

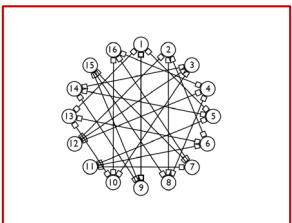
Question 2:

Given This Structure,
What Can Be Achieved?
Metrics and Algorithms?

A first insight: entropy of the demand.

Models and Connection to Datastructures & Coding

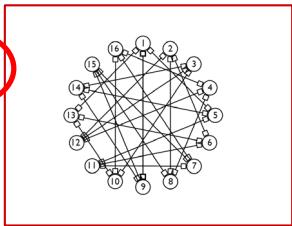
Oblivious networks
(worst-case traffic)



More structure: **lower routing cost**

Models and Connection to Datastructures & Coding

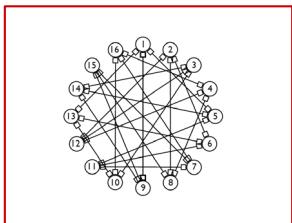
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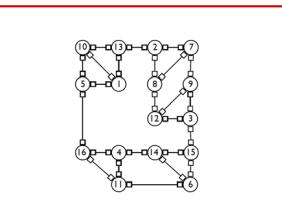
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Models and Connection to Datastructures & Coding

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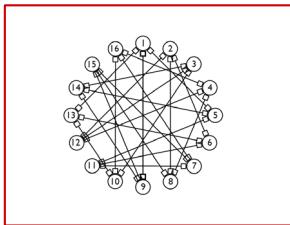
Demand-aware networks
(spatial structure)



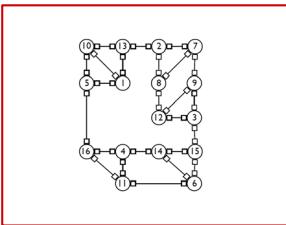
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Models and Connection to Datastructures & Coding

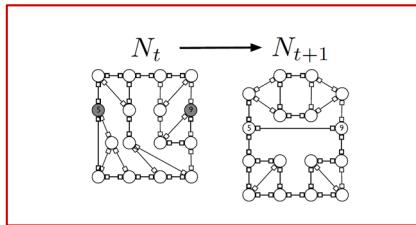
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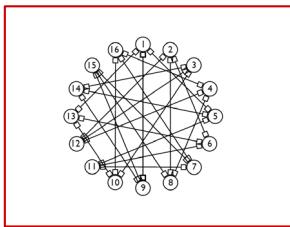
Self-adjusting networks
(temporal structure)



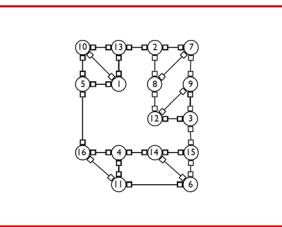
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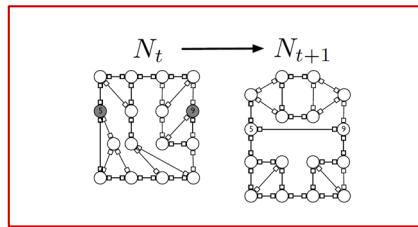
Oblivious networks
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Demand-aware networks
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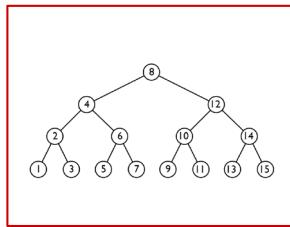


Self-adjusting networks
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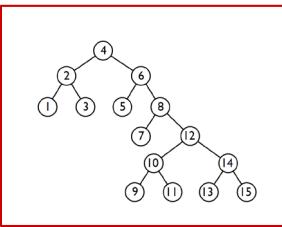


More structure: **lower routing cost**

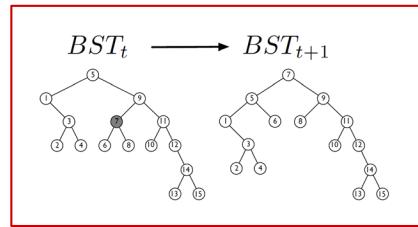
Traditional BST
(Worst-case coding)



Demand-aware BST
(Huffman coding)



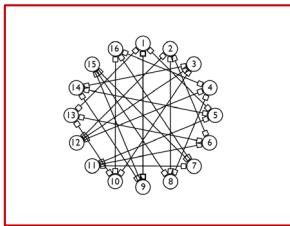
Self-adjusting BST
(Dynamic Huffman coding)



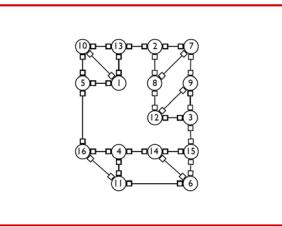
More structure: improved **access cost** / shorter **codes**

Models and Connection to Datastructures & Coding

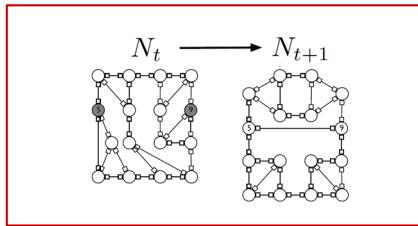
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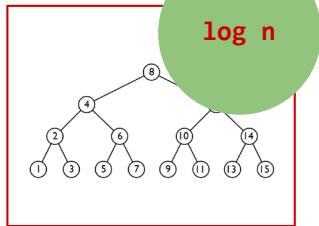


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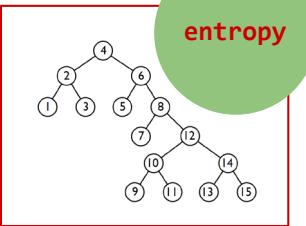


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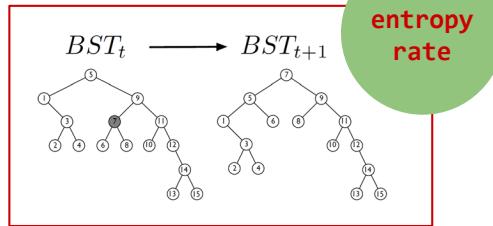
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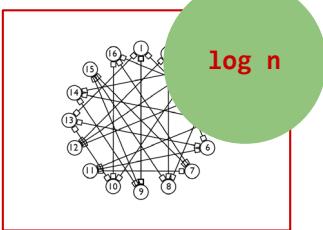
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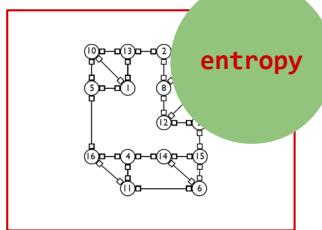
More structure: improved **access cost** / shorter **codes**

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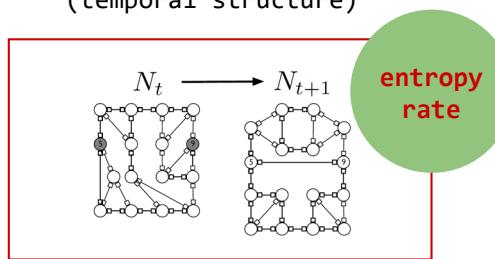
Traditional networks
(worst-case traffic)



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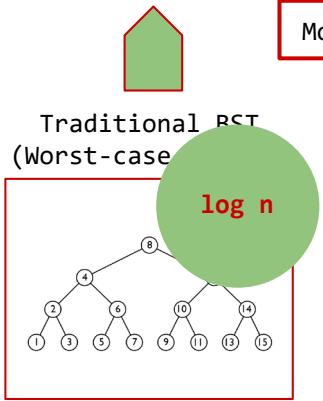


Self-adjusting networks
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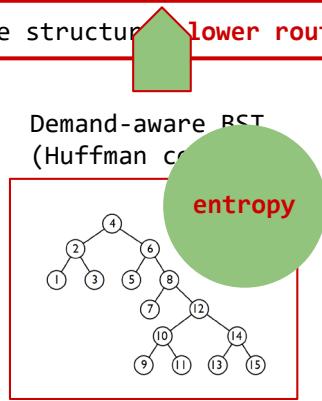


More than
an analogy!

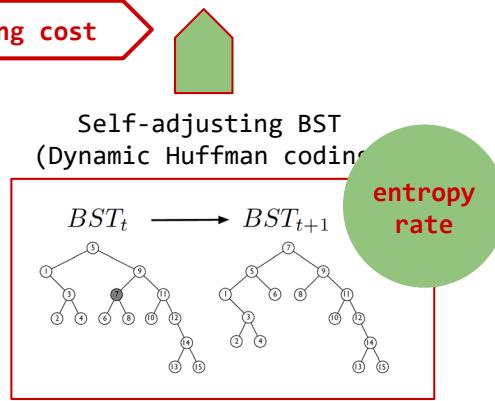
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More structure: improved **access cost** / shorter **codes**

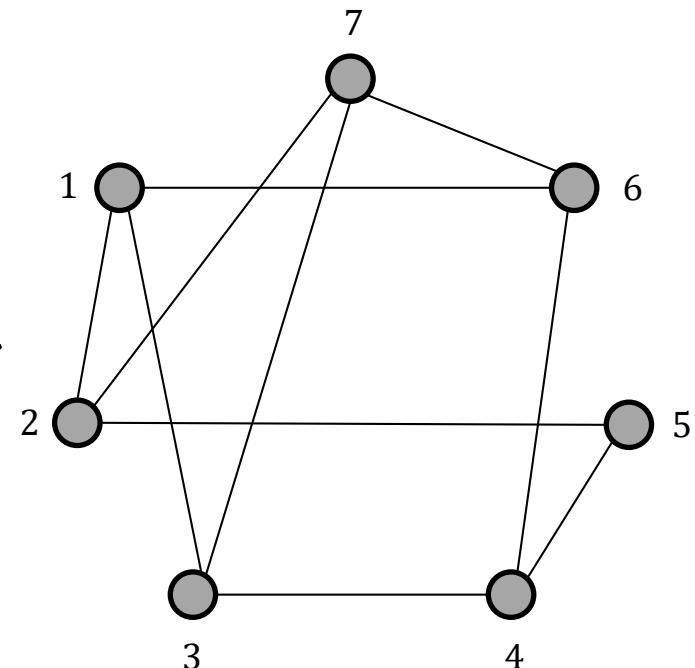
Generalize methodology:
... and transfer
entropy bounds and
algorithms of data-
structures to networks.

First result:
Demand-aware networks
of asymptotically
optimal route lengths.

Case Study “Route Lengths”

Constant-Degree Demand-Aware Network

		Destinations							
		1	2	3	4	5	6	7	
Sources		1	0	$\frac{2}{65}$	$\frac{1}{13}$	$\frac{1}{65}$	$\frac{1}{65}$	$\frac{2}{65}$	$\frac{3}{65}$
2		$\frac{2}{65}$	0	$\frac{1}{65}$	0	0	0	$\frac{2}{65}$	
3		$\frac{1}{13}$	$\frac{1}{65}$	0	$\frac{2}{65}$	0	0	$\frac{1}{13}$	
4		$\frac{1}{65}$	0	$\frac{2}{65}$	0	$\frac{4}{65}$	0	0	
5		$\frac{1}{65}$	0	$\frac{3}{65}$	$\frac{4}{65}$	0	0	0	
6		$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$	
7		$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0	



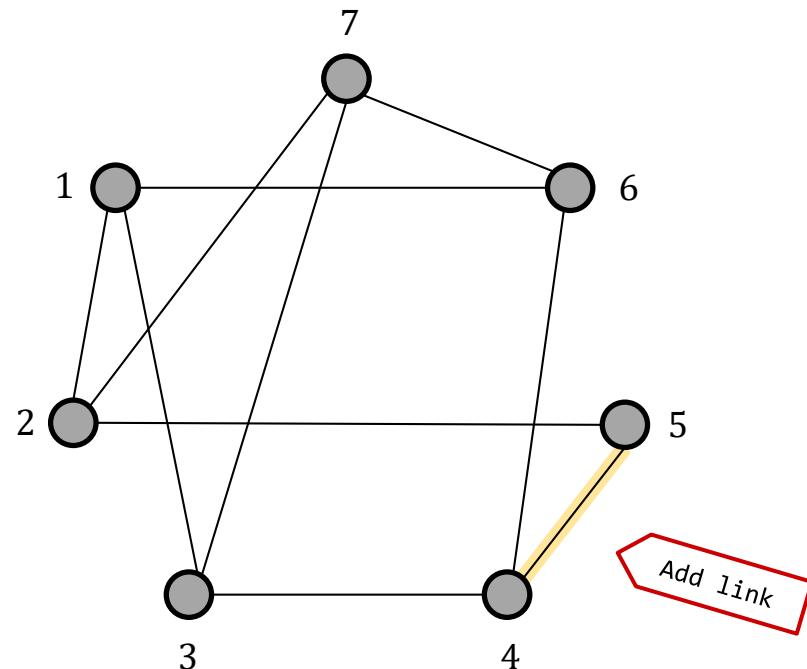
$$\text{ERL}(\mathcal{D}, N) = \sum_{(u,v) \in \mathcal{D}} p(u, v) \cdot d_N(u, v)$$

Case Study “Route Lengths”

Constant-Degree Demand-Aware Network

		Destinations						
		1	2	3	4	5	6	7
Sources	1	0	$\frac{2}{65}$	$\frac{1}{13}$	$\frac{1}{65}$	$\frac{1}{65}$	$\frac{2}{65}$	$\frac{3}{65}$
	2	$\frac{2}{65}$	0	$\frac{1}{65}$	0	0	0	$\frac{2}{65}$
	3	$\frac{1}{13}$	$\frac{1}{65}$	0	$\frac{2}{65}$	0	0	$\frac{1}{13}$
	4	$\frac{1}{65}$	0	$\frac{2}{65}$	0	$\frac{4}{65}$	0	0
	5	$\frac{1}{65}$	0	$\frac{3}{65}$	0	0	0	0
	6	$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$
	7	$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0

Much from 4 to 5



$$\text{ERL}(\mathcal{D}, N) = \sum_{(u,v) \in \mathcal{D}} p(u, v) \cdot d_N(u, v)$$

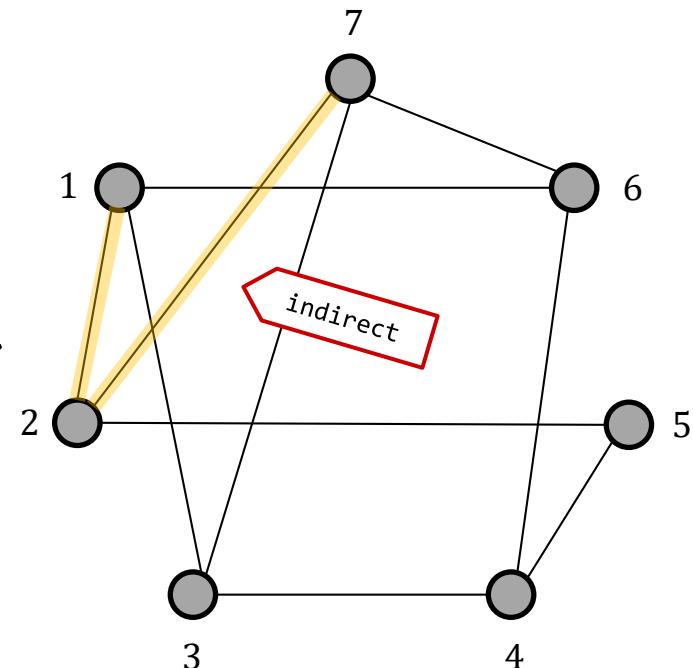
Case Study “Route Lengths”

Constant-Degree Demand-Aware Network

communicate
d with many

Destinations

	1	2	3	4	5	6	7
1	0	$\frac{2}{65}$	$\frac{1}{13}$	$\frac{1}{65}$	$\frac{1}{65}$	$\frac{2}{65}$	$\frac{3}{65}$
2	$\frac{2}{65}$	0	$\frac{1}{65}$	0	0	0	$\frac{2}{65}$
3	$\frac{1}{13}$	$\frac{1}{65}$	0	$\frac{2}{65}$	0	0	$\frac{1}{13}$
4	$\frac{1}{65}$	0	$\frac{2}{65}$	0	$\frac{4}{65}$	0	0
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6	$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$
7	$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0



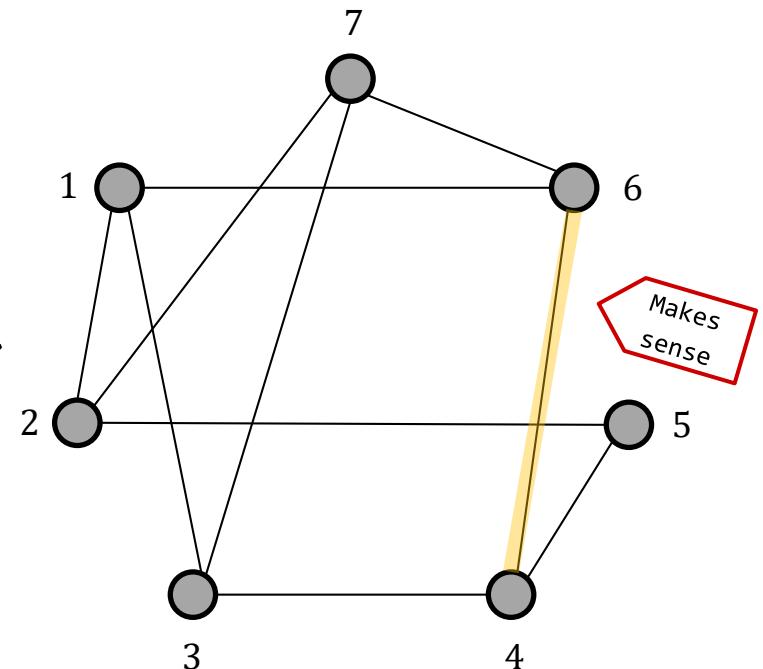
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Case Study “Route Lengths”

Constant-Degree Demand-Aware Network

		Destinations							
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Sources		1	0	$\frac{2}{65}$	$\frac{1}{13}$	$\frac{1}{65}$	$\frac{1}{65}$	$\frac{2}{65}$	$\frac{3}{65}$
		2	$\frac{2}{65}$	0	$\frac{1}{65}$	0	0	0	$\frac{2}{65}$
		3	$\frac{1}{13}$	$\frac{1}{65}$	0	$\frac{1}{65}$	0	0	$\frac{1}{13}$
		4	$\frac{1}{65}$	0	$\frac{2}{65}$	0	$\frac{1}{65}$	0	0
		5	$\frac{1}{65}$	0	$\frac{3}{65}$	$\frac{4}{65}$	0	0	0
		6	$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$
		7	$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0

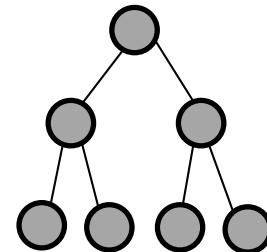
Don't communicate



$$\text{ERL}(\mathcal{D}, N) = \sum_{(u,v) \in \mathcal{D}} p(u, v) \cdot d_N(u, v)$$

Examples

- DAN for $\Delta=3$
 - E.g., complete **binary tree** would be **$\log n$**
 - Can we do better?

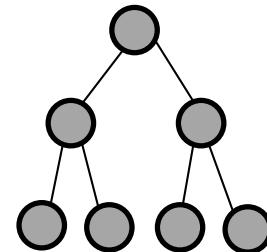


- DAN for $\Delta=2$
 - set of **lines** and **cycles**



Examples

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- DAN for $\Delta=2$
 - set of **lines** and **cycles**

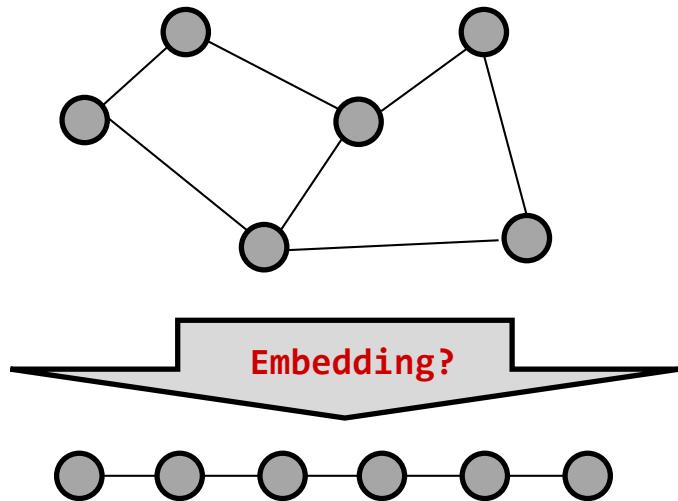


How
hard?

Related Problem

Virtual Network Embedding Problem (VNEP)

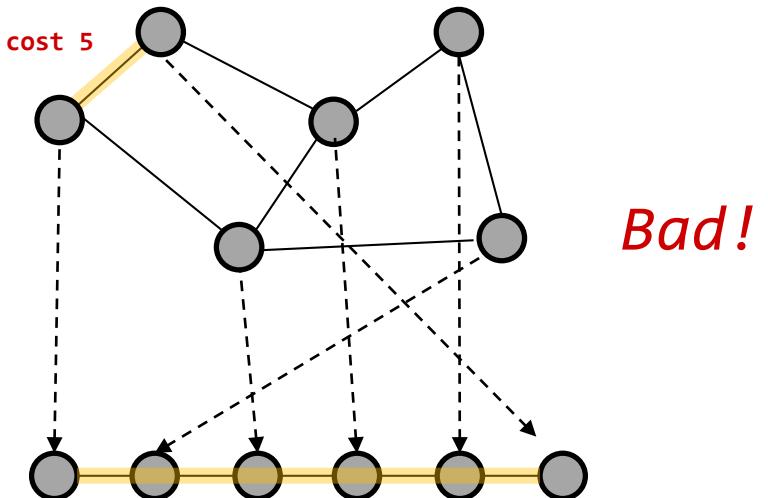
Example $\Delta=2$: A Minimum Linear Arrangement (MLA) Problem
→ Minimizes sum of virtual edges



Related Problem

Virtual Network Embedding Problem (VNEP)

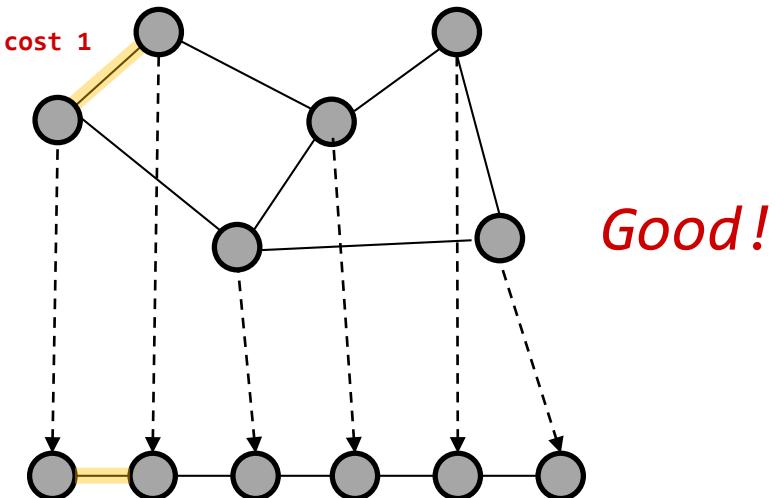
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Related Problem

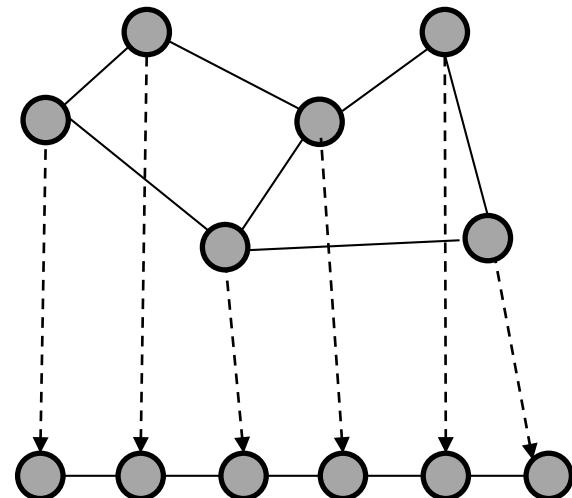
Virtual Network Embedding Problem (VNEP)

Example $\Delta=2$: A Minimum Linear Arrangement (MLA) Problem

→ Minimizes sum of virtual edges

MLA is **NP-hard**

→ ... and so is our problem!



Related Problem

Virtual Network Embedding Problem (VNEP)

Example $\Delta=2$: A Minimum Linear Arrangement (MLA) Problem

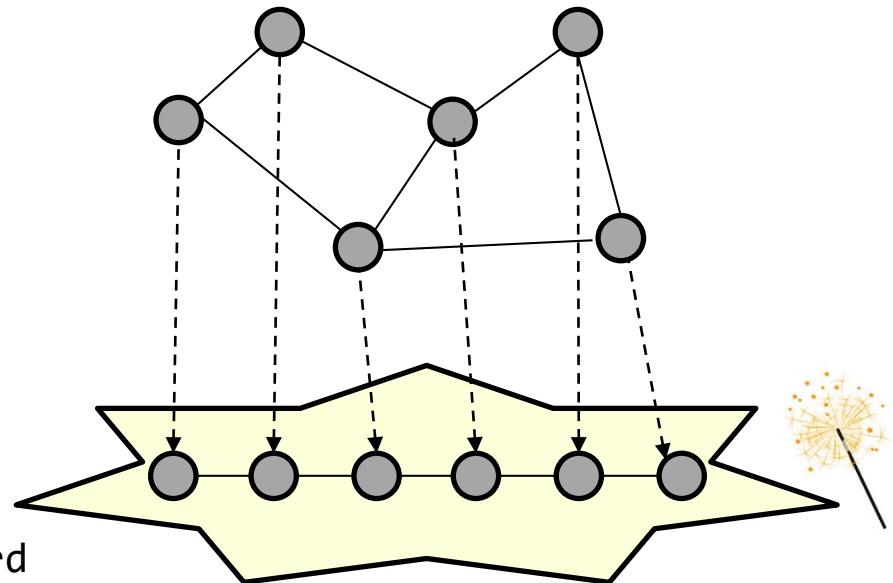
- Minimizes sum of virtual edges

MLA is **NP-hard**

- ... and so is our problem!

But what about $\Delta > 2$?

- Embedding problem still hard
- But we have a new **degree of freedom!**



Related Problem

Virtual Network Embedding Problem (VNEP)

Example $\Delta=2$: A Minimum Linear Arrangement (MLA) Problem

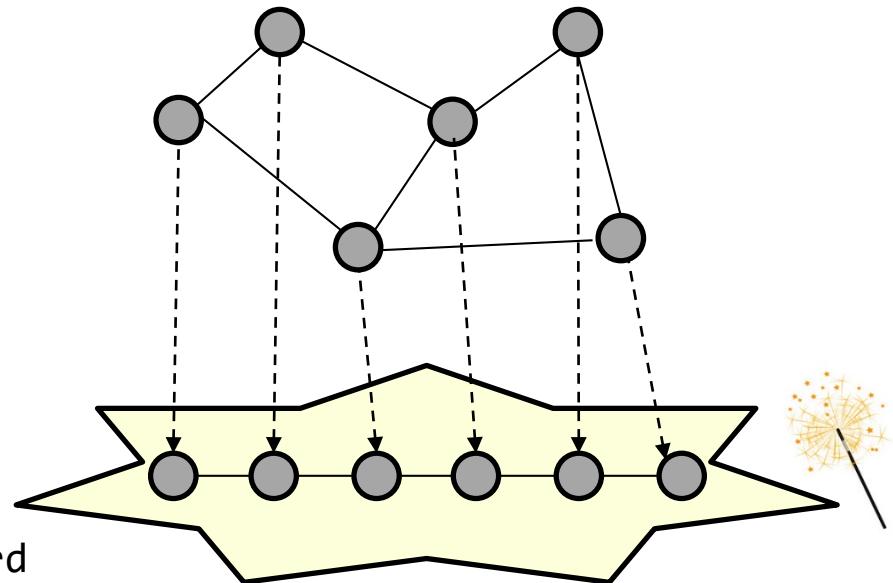
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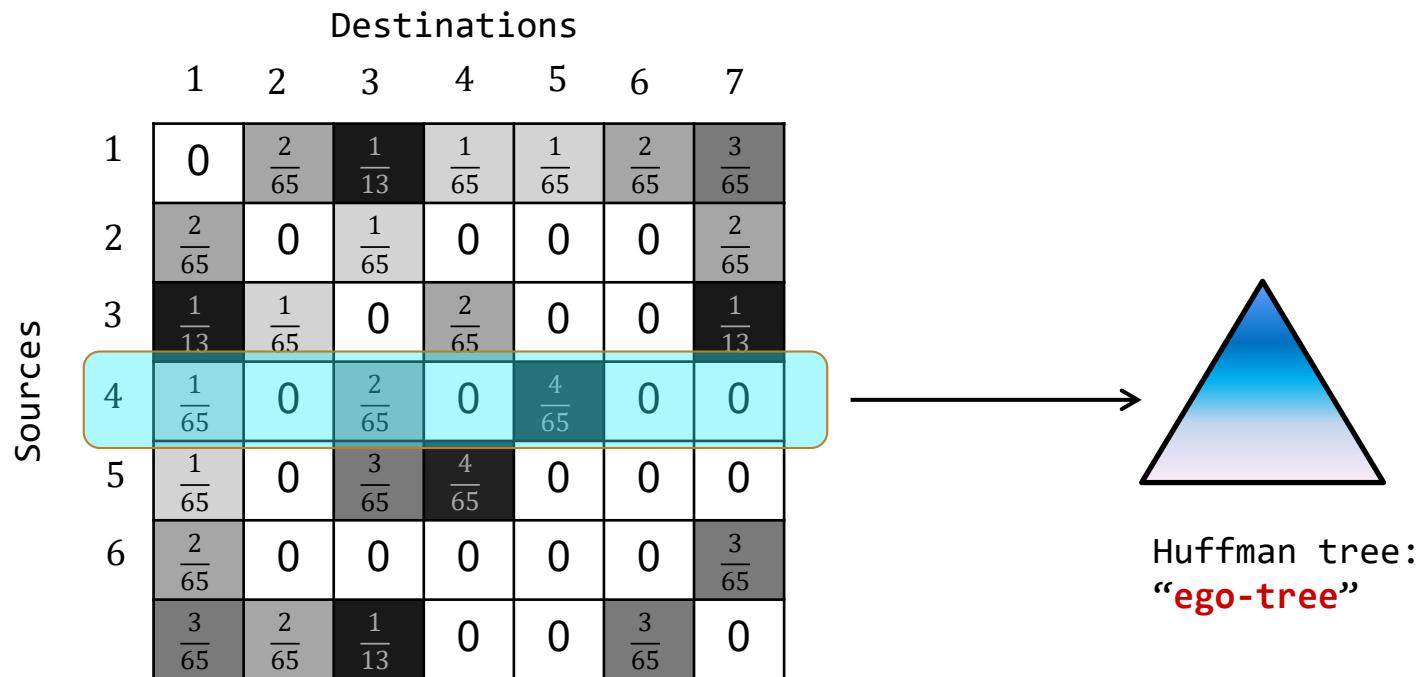
But what about $\Delta > 2$?

- Embedding problem still hard
- But we have a new **degree of freedom!**



Simplifies problem?!

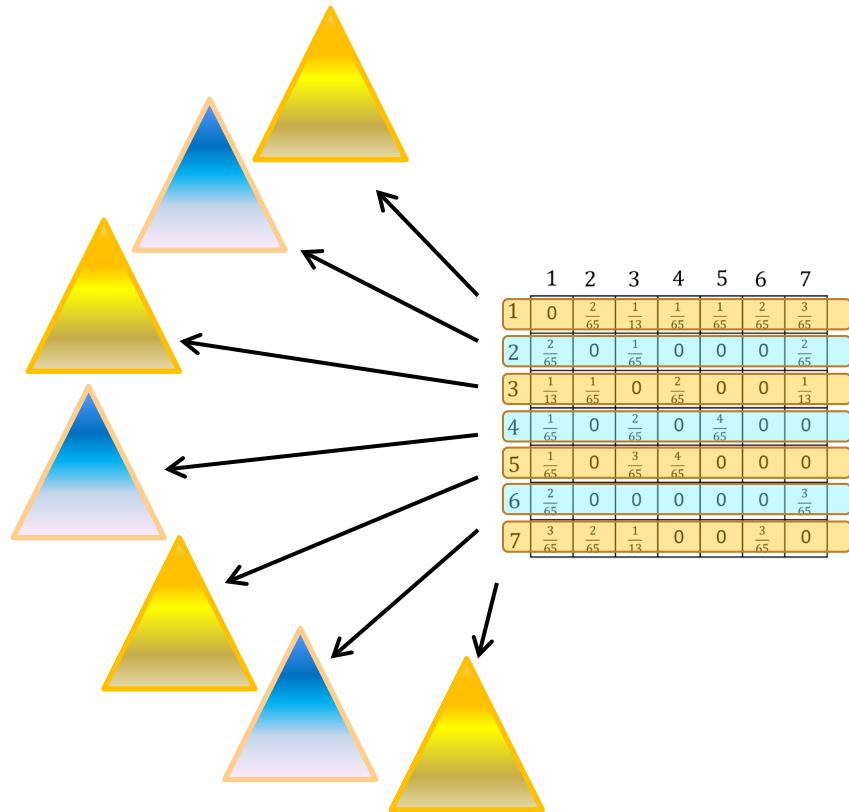
Entropy Lower Bound



Entropy Lower Bound

$$\text{ERL} = \Omega(H_{\Delta}(Y|X))$$

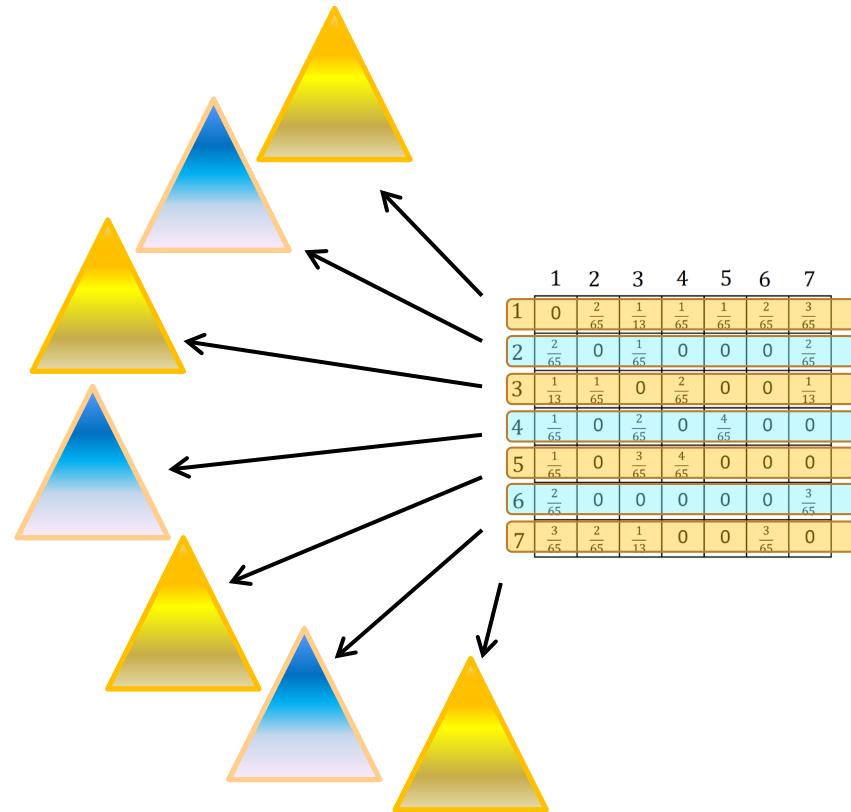
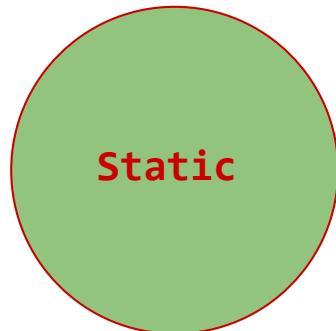
destinations sources
degree



Entropy Upper Bound

→ Idea for algorithm:

- union of trees
- reduce degree
- but keep distances



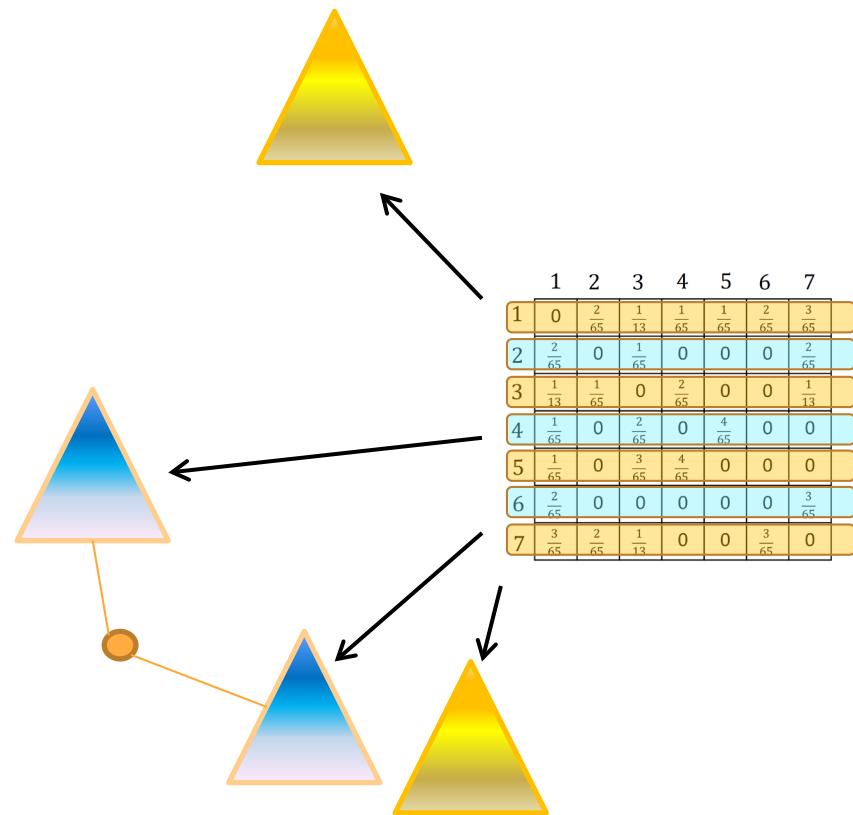
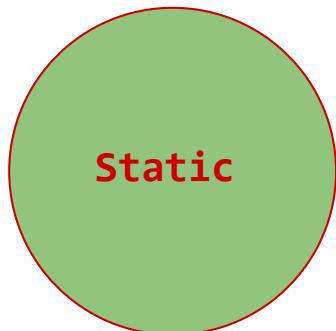
Entropy Upper Bound

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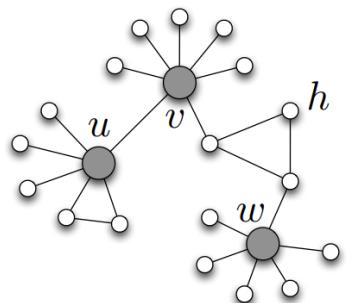
→ Ok for sparse demands

- not everyone gets tree
- helper nodes

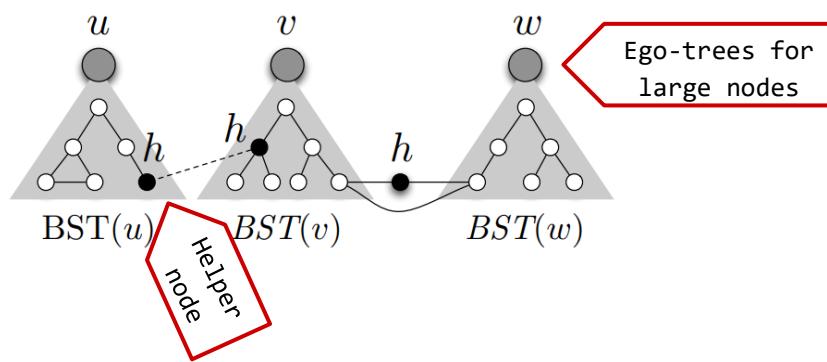


Intuition of Algorithm

Demand graph:

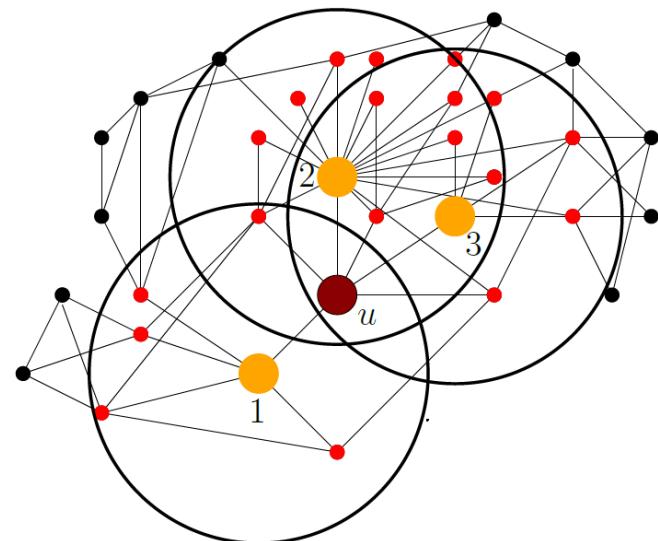


Demand-aware network:



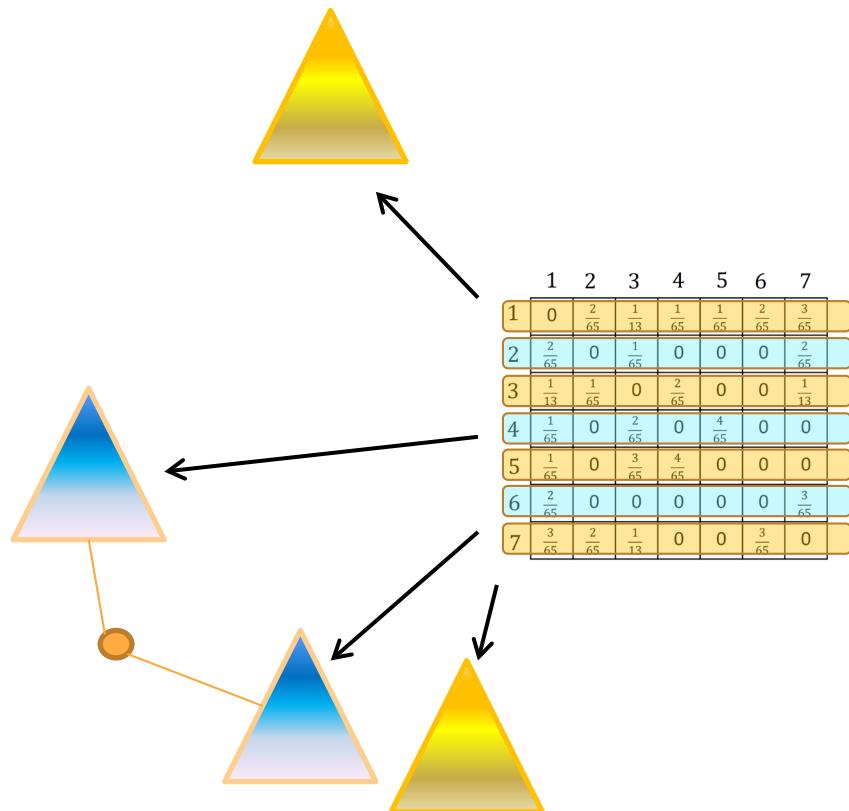
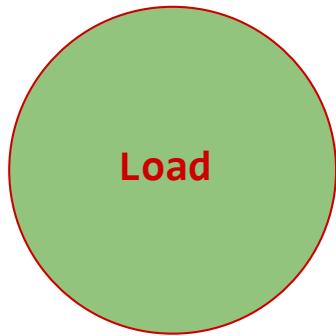
More Optimal Graphs

- For regular and uniform demands which admit constant distortion linear spanner
- Graphs of **bounded doubling dimension**



Accounting for Load

- … Still use **ego-trees**
- … But balance for **load**



Further Reading

TON 2016, DISC 2017, CCR 2019, INFOCOM 2019

Demand-Aware Network Designs of Bounded Degree*

Chen Avin¹, Kaushik Mondal¹, and Stefan Schmid²

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2 Department of Computer Science
Aalborg University, Denmark
schmiste@cs.aau.dk

Abstract

Traditionally, networks such as datacenter interconnects are designed to optimize worst-case performance under *arbitrary* traffic patterns. Such network designs can however be far from optimal when considering the *actual* workloads and traffic patterns which they serve. This insight led to the development of demand-aware datacenter interconnects which can be reconfigured depending on the workload.

Motivated by these trends, this paper initiates the algorithmic study of demand-aware networks (DANs), and in particular the design of bounded-degree networks. The inputs to the network

Toward Demand-Aware Networking: A Theory for Self-Adjusting Networks

Chen Avin
Ben Gurion University, Israel
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Stefan Schmid
University of Vienna, Austria
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This article is an editorial note submitted to CCR. It has NOT been peer reviewed.
The authors take full responsibility for this article's technical content. Comments can be posted through CCR Online.

ABSTRACT

The physical topology is emerging as the next frontier in an ongoing effort to render communication networks more flexible. While first empirical results indicate that these flexibilities can be exploited to reconfigure and optimize the network toward the workload it serves and, e.g., providing the same bandwidth at lower infrastructure cost, only little is known today about the fundamental algorithmic problems underlying the design of reconfigurable networks. This paper initiates the study of the theory of demand-aware, self-adjusting networks. Our main position is that self-adjusting networks should be seen through the lens of self-adjusting data-



Figure 1: Taxonomy of topology optimization

design of efficient datacenter networks has received much attention over the last years. The topologies underlying mod-

SplayNet: Towards Locally Self-Adjusting Networks

Stefan Schmid*, Chen Avin*, Christian Scheideler, Michael Borokhovich, Bernhard Haeupler, Zvi Lotker

Abstract—This paper initiates the study of locally self-adjusting networks: networks whose topology adapts dynamically and in a decentralized manner, to the communication pattern σ . Our vision can be seen as a distributed generalization of the self-adjusting datastructures introduced by Sleator and Tarjan [22]. In contrast to their splay trees which dynamically optimize the lookup costs from a single node (namely the tree root), we seek to minimize the routing cost between arbitrary communication pairs in the network.

As a first step, we study distributed binary search trees (BSTs), which are attractive for their support of greedy routing. We introduce a simple model which captures the fundamental tradeoff between the benefits and costs of self-adjusting networks. We present the SplayNet algorithm and formally analyze its performance, and prove its optimality in specific case studies. We also introduce lower bound techniques based on interval cuts and

toward static metrics, such as the diameter or the length of the longest route; the self-adjusting paradigm has not spilled over to distributed networks yet.

We, in this paper, initiate the study of a distributed generalization of self-optimizing datastructures. This is a non-trivial generalization of the classic splay tree concept. While in classic BSTs, *lookup request* always originates from the same node, the tree root, distributed datastructures and networks such as skip graphs [2], [13] have to support *routing requests* between arbitrary pairs (or *peers*) of communicating nodes; in other words, both the source as well as the destination of the requests become variable. Figure 1 illustrates the difference between classic and distributed binary search trees.

In this paper, we ask: Can we gain similar benefits from self-

Demand-Aware Network Design with Minimal Congestion and Route Lengths

Chen Avin
Communication Systems Engineering Dept.
Ben Gurion University of the Negev, Israel

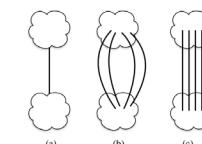
Kaushik Mondal
Communication Systems Engineering Dept.
Ben Gurion University of the Negev, Israel

Stefan Schmid
Faculty of Computer Science
University of Vienna, Austria

Abstract—Emerging communication technologies allow to reconfigure physical network topologies at runtime, enabling demand-aware networks (DANs); networks whose topology is optimized toward the workload they serve. However, today only little is known about the fundamental algorithmic problems underlying the design of DANs. This paper initiates the study of DANs, which minimizes both congestion and route lengths. The designed network is a *skip graph*: communication sources arrange individually, we show that there exist any bounded-degree networks (building sets provide lower bounds on the density of the links). The main building block of the designed *d*-DANs networks are *ego-trees*: communication sources arrange their communication partners in an optimal tree, *individually*. When the union of these ego-trees forms the basic structure of *d*-DANs, further techniques are presented to ensure bounded degrees (for scalability).

I. INTRODUCTION

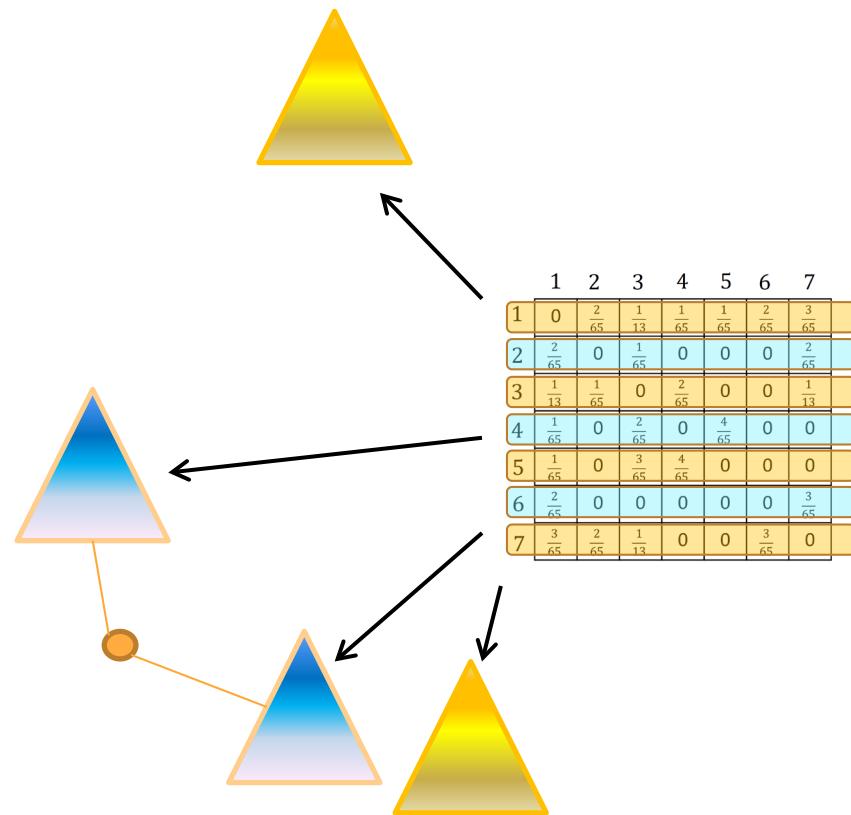
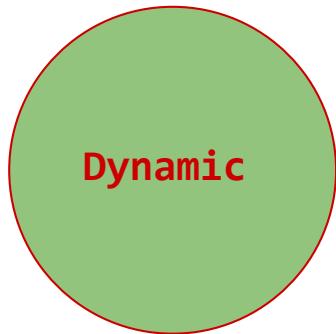
A. Motivation
Data center networks have become a critical infrastructure of our digital society. With the trend toward more data-intensive applications, data center network traffic is growing quickly [7], [13]. As much of this traffic is *internal* to the data center (e.g.,



However, only little is known today about the algorithmic challenge of designing demand-aware networks which provide low congestion and short routes (in the number of hops), for

Dynamic Setting

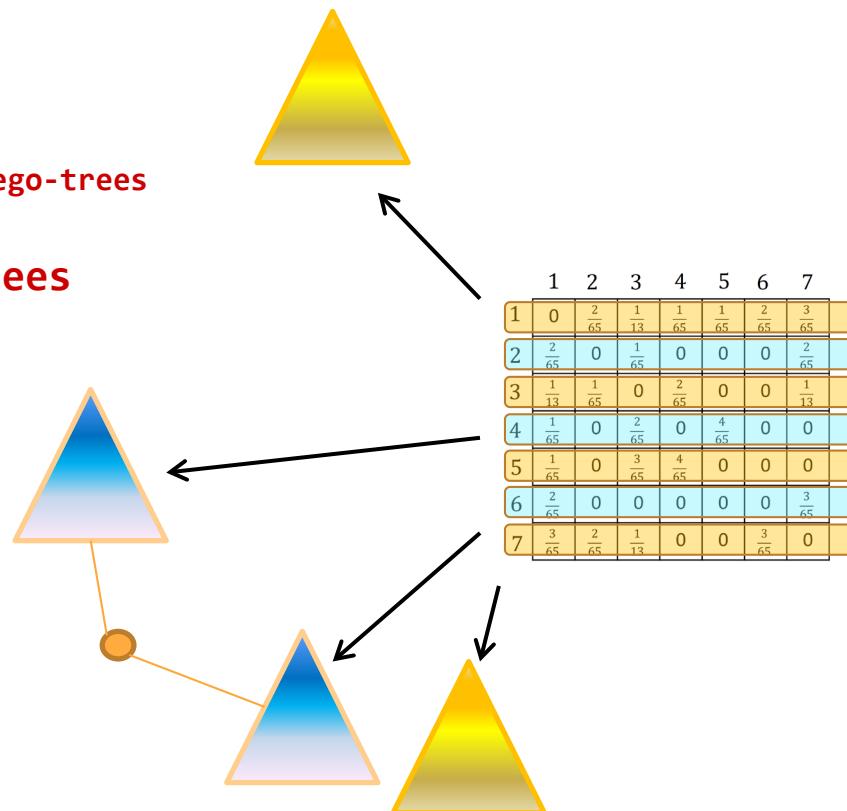
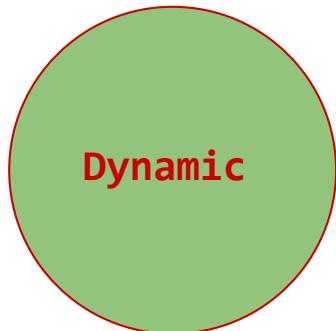
- Dynamic the same:
 - union of **dynamic ego-trees**
- E.g., SplayNets
- **Online algorithms**



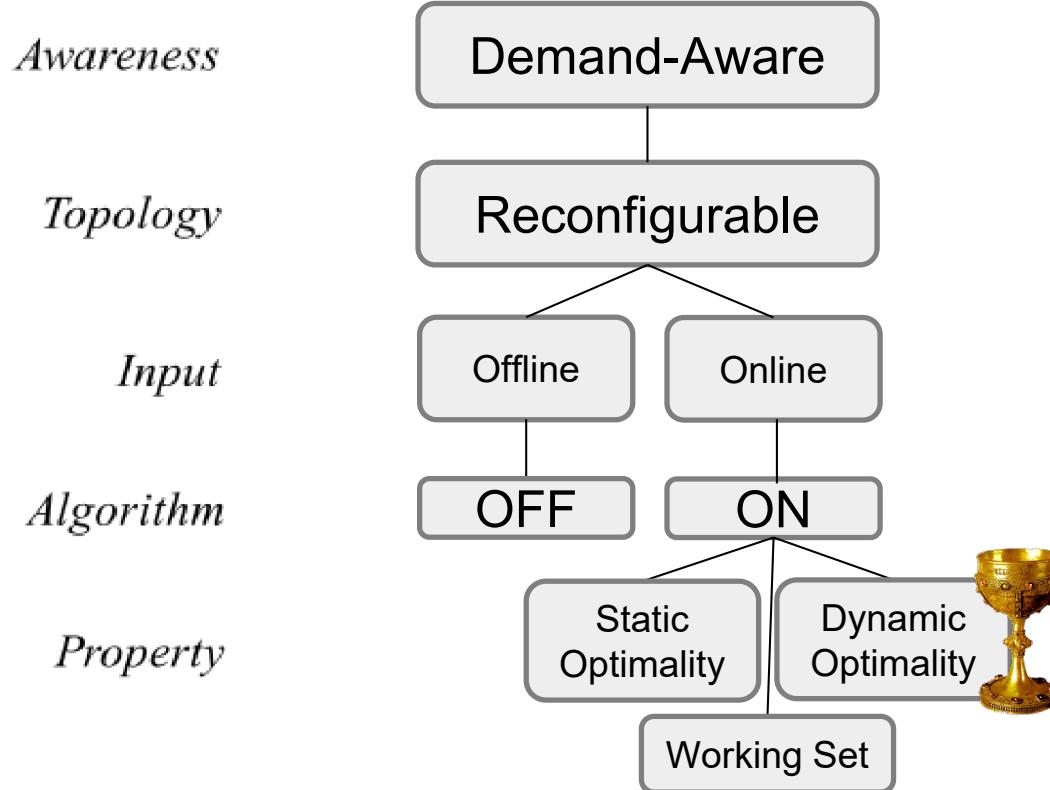
Dynamic Setting

& distributed

- Dynamic the same:
 - union of **dynamic&distributed ego-trees**
- E.g., SplayNets or **CB trees**
- **Online algorithms**

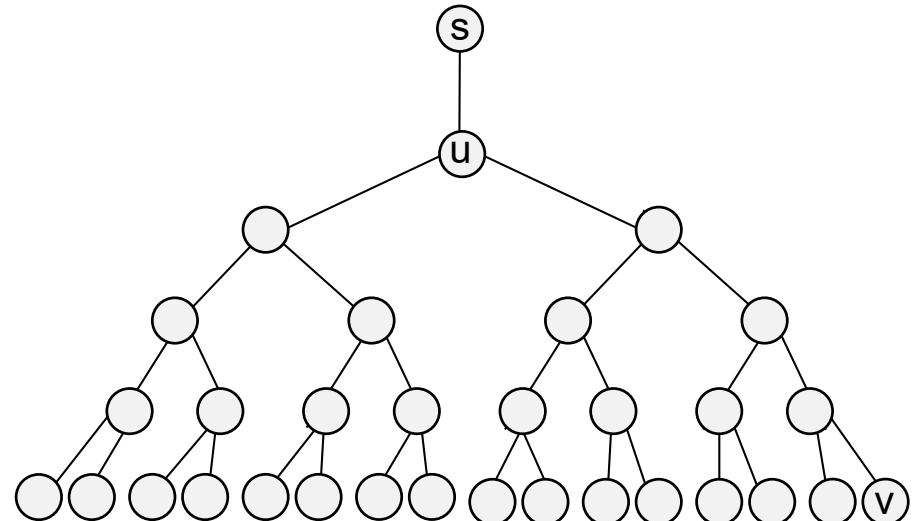


Dynamic Objectives



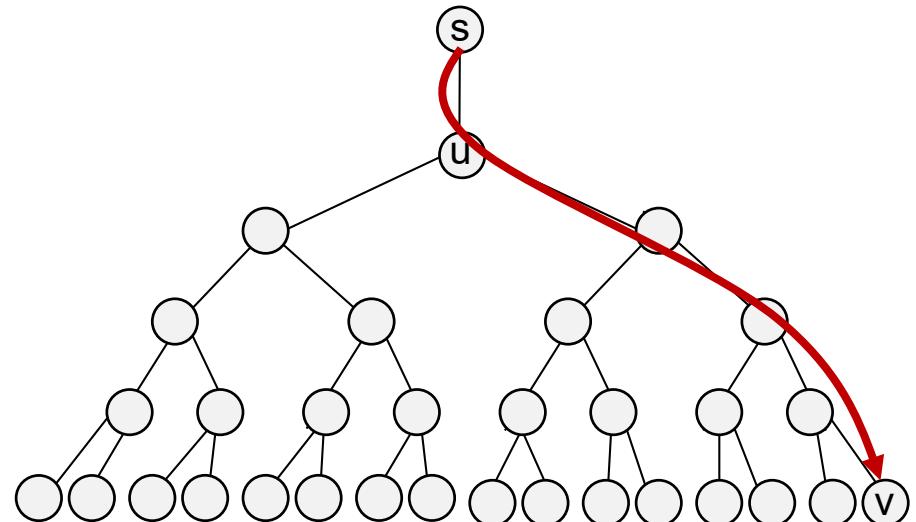
Dynamic Optimality: Push-Down Trees

- For unordered search trees, dynamic optimality is possible: **Push-Down Trees**
- Useful property: **most recently used (MRU)**



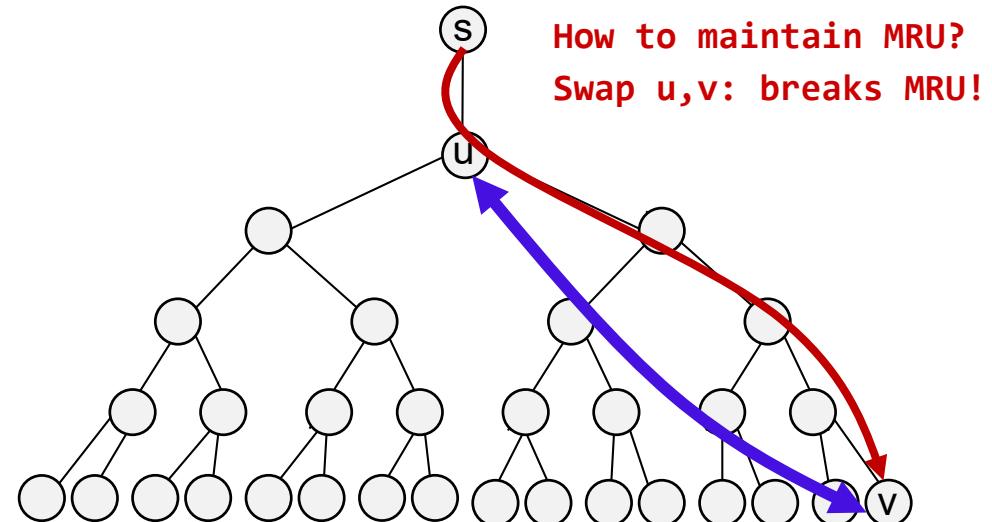
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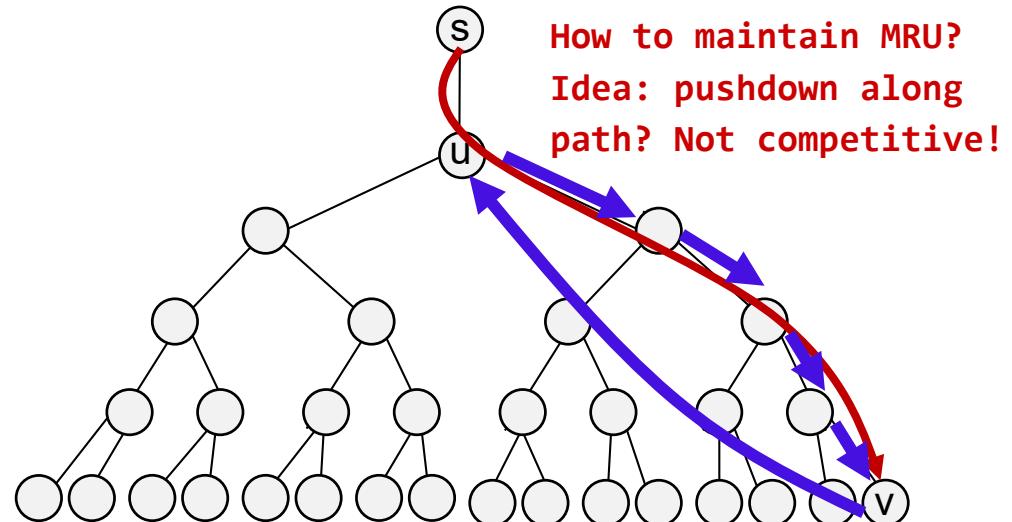
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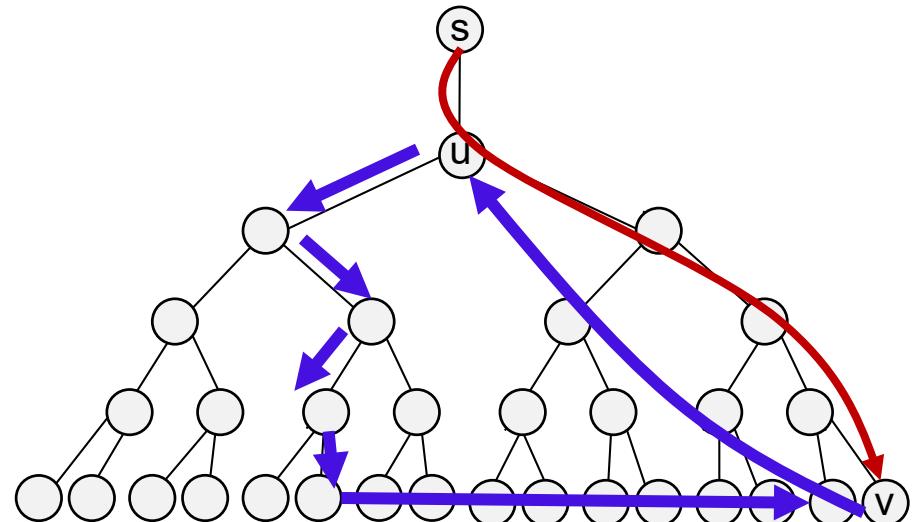
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Dynamic Optimality: Push-Down Trees

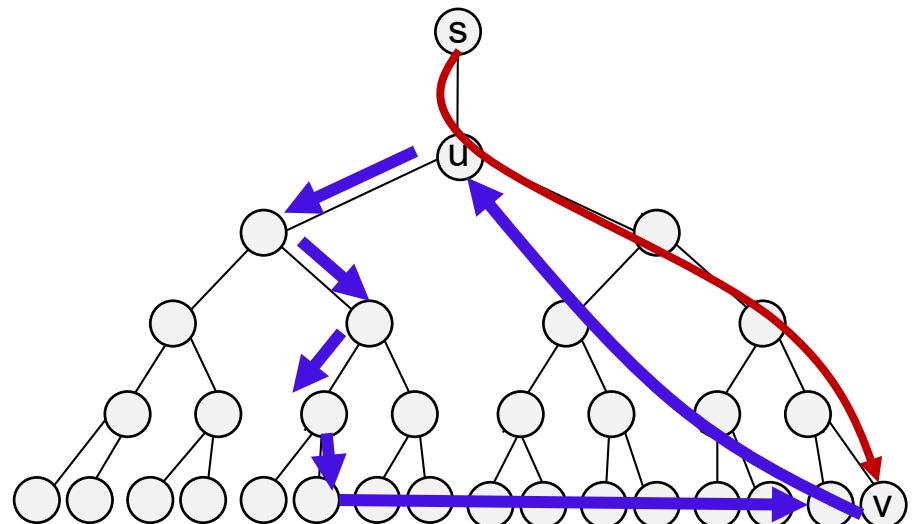
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- Idea: **balanced** pushdown (random vs deterministic?)



Dynamic Optimality: Push-Down Trees

- For unordered search trees, dynamic optimality is possible: **Push-Down Trees**
- Useful property: **most recently used (MRU)**
- Idea: **balanced** pushdown (random vs deterministic?)

Random walk preserves MRU!
Constant competitive.
Deterministic does not.
Still constant competitive?



Further Reading

LATIN 2020, IPDPS 2021

Dynamically Optimal Self-Adjusting Single-Source Tree Networks

Chen Avin¹, Kaushik Mondal², and Stefan Schmid³

¹ Ben Gurion University of the Negev, Israel

² Indian Institute of Technology Ropar, India

³ Faculty of Computer Science, University of Vienna, Austria

Abstract. This paper studies a fundamental algorithmic problem related to the design of demand-aware networks: networks whose topologies adjust toward the traffic patterns they serve, in an online manner. The goal is to strike a tradeoff between the benefits of such adjustments (shorter routes) and their costs (reconfigurations). In particular, we consider the problem of designing a self-adjusting tree network which serves single-source, multi-destination communication. The problem has

CBNet: Minimizing Adjustments in Concurrent Demand-Aware Tree Networks

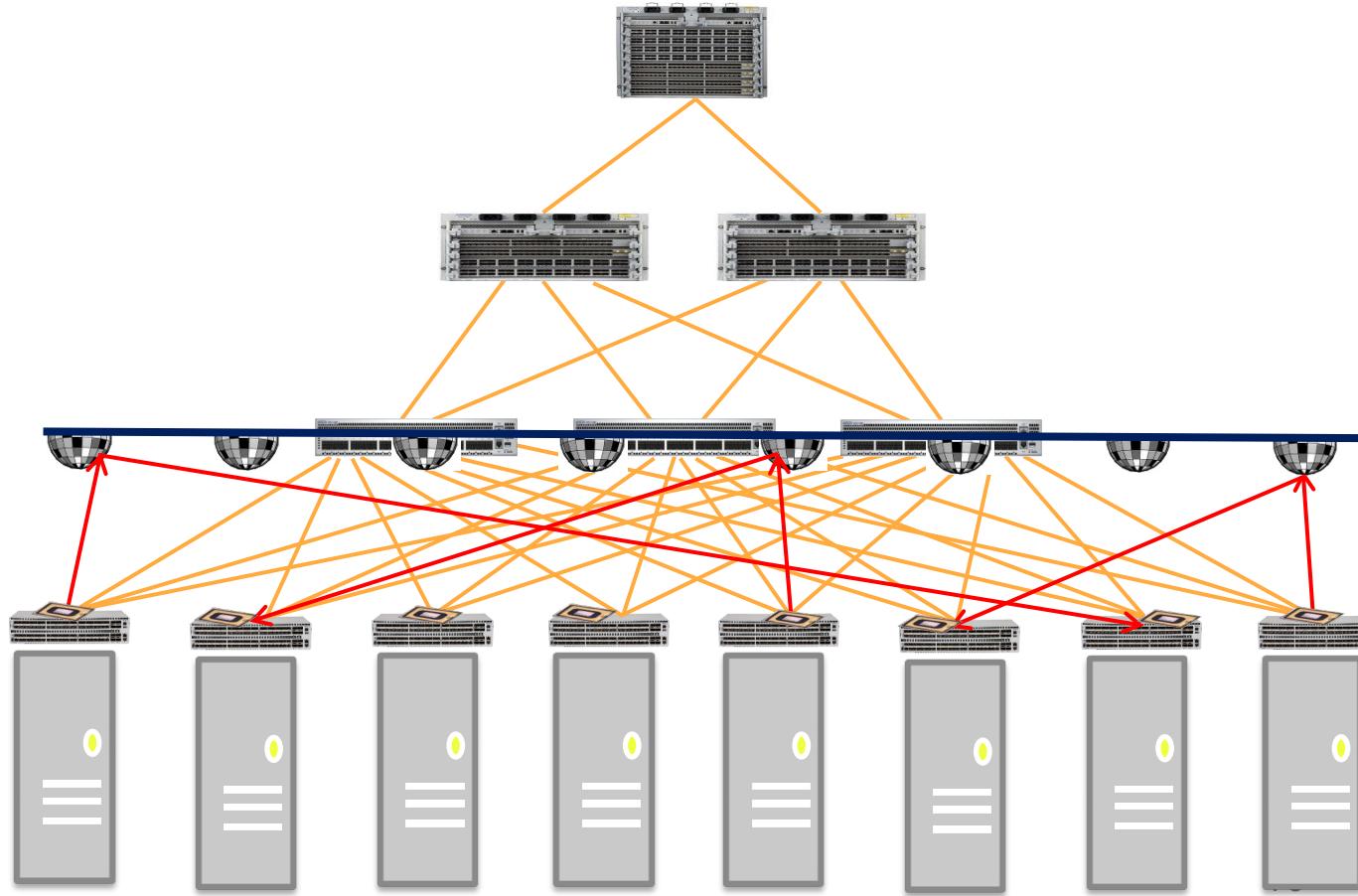
Otavio Augusto de Oliveira Souza¹ Olga Goussevskaia¹ Stefan Schmid²
¹ Universidade Federal de Minas Gerais, Brazil ² University of Vienna, Austria

Abstract—This paper studies the design of demand-aware network topologies: networks that dynamically adapt themselves toward the demand they currently serve, in an online manner. While demand-aware networks may be significantly more efficient than demand-oblivious networks, frequent adjustments are still costly. Furthermore, a centralized controller of such networks may become a bottleneck.

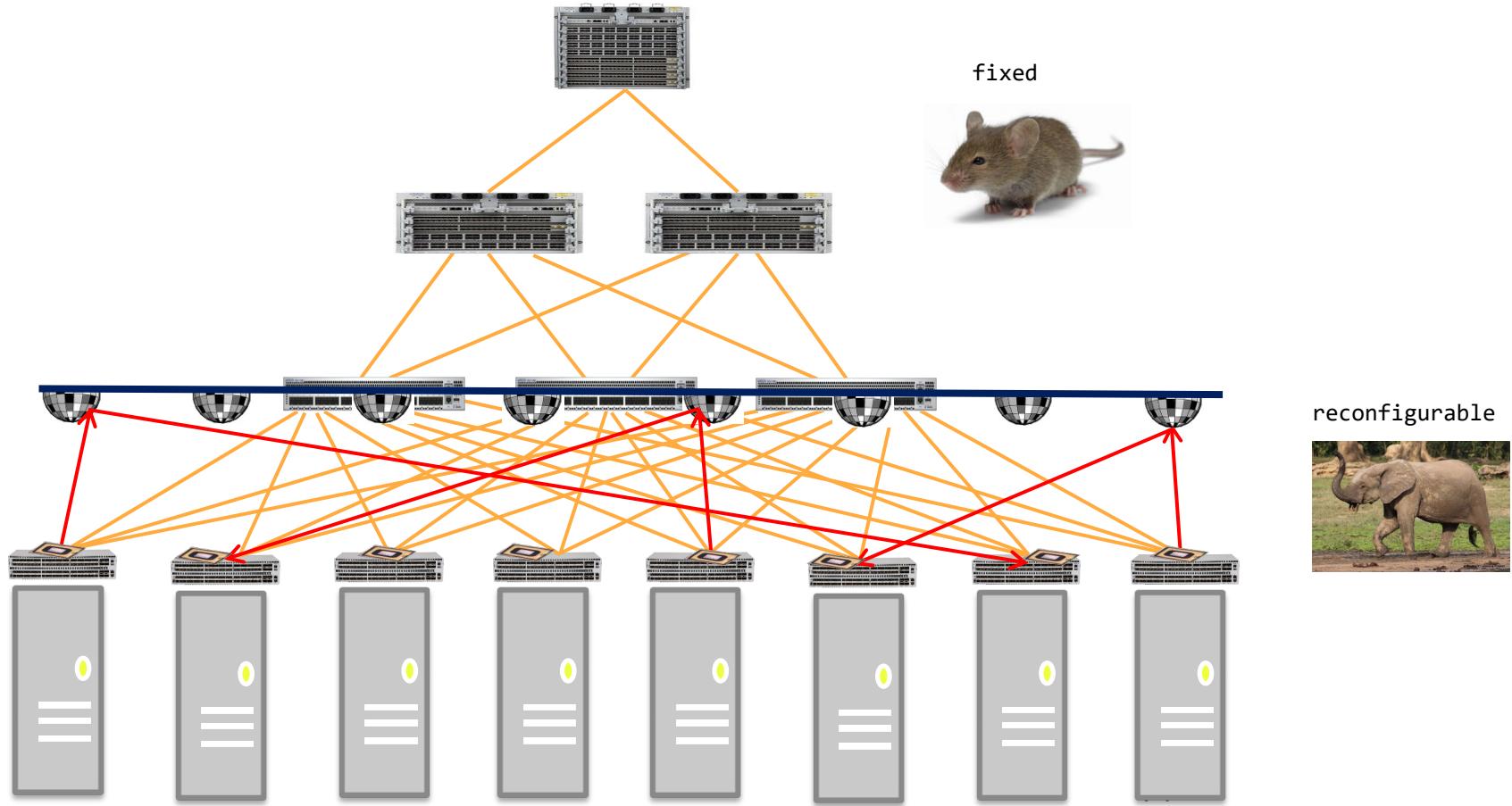
We present CBNet (Counting-Based self-adjusting Network), a

CBNet is based on concepts from self-adjusting data structures, and in particular, CBTrees [12]. CBNet gradually adapts the network topology toward the communication pattern in an online manner, i.e., without previous knowledge of the demand distribution. At the same time, *bidirectional semi-splaying* and counters are used to maintain state, minimize reconfiguration costs and maximize concurrency.

Hybrid Networks



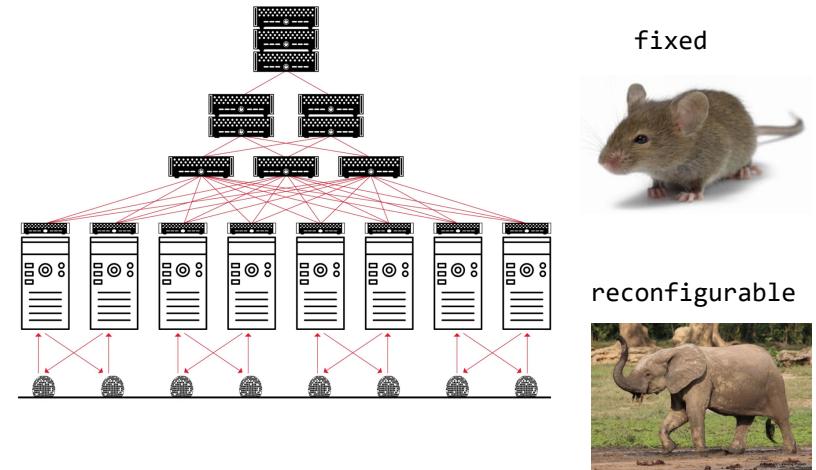
Hybrid Networks



ReNet

A Statically Optimal Demand-Aware Network

- Model: **hybrid architecture**
 - Fixed network of diameter $\log n$ plus reconfigurable network (**constant** number of direct links)
 - **Segregated** routing
 - **Online** sequence of requests:
 $\sigma = (\sigma_1, \sigma_2, \sigma_3, \dots)$
 - Global controller
- **Objective:** Minimize route length plus reconfigurations
 - More specifically:
be **statically optimal**
 - Compared to a fixed algorithm which knows σ ahead of time



- Compact routing (constant tables)
- Local routing (greedy)
- Arbitrary addressing

The ReNet Algorithm (1)

Algorithmic building blocks:

1. Working Set (WS)

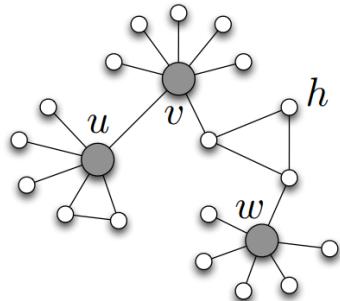
→ Nodes keep track of recent communication partners in σ .

2. Small/large nodes and Ego-Tree

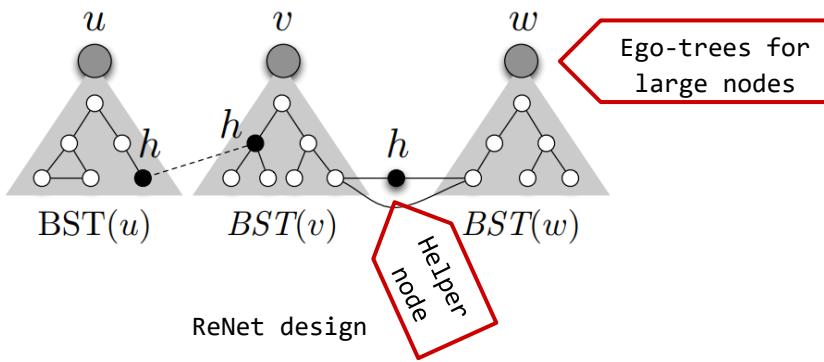
→ Nodes with small WS connect to WS directly, nodes with large WS via a self-adjusting binary search tree (e.g., a **splay tree**)

3. Helper nodes to reduce the degree

→ Large nodes may appear in many ego-trees, so get help of small nodes



Demand graph



ReNet design

The ReNet Algorithm (2)

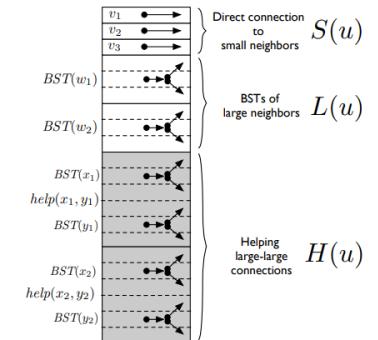
Continued:

4. Self adjustments

- Keep track of WS; when too large: **flush-when-full**

5. Centralized coordination

- Fairly **decentralized**: coordinator only needs to keep track of which nodes are large and which small
- Nodes inform coordinator when adding node to working set
- Coordinator then assigns helper node on demand



Analytical Results (1)

Theorem 1:

For any **sparse** communication sequence of a certain length, ReNets are statically optimal while ensuring a bounded degree.

- Sparse: subsequences of only involve a linear number of nodes
- Required to ensure availability of helper nodes (DISC 2017)

Analytical Results (2)

Theorem 2:

Under certain communication patterns, the amortized cost of ReNet can be significantly lower than the static optimum, i.e., $\Omega(\log n)$.

- Example: consider sequence of $\sigma = (\sigma^{(1)}, \sigma^{(2)}, \sigma^{(3)}, \dots)$ where each $\sigma^{(i)}$ is of length $n \log n$, sparse and corresponds to different **2-dimensional grid**.
- In this example, the cost of ReNet is **constant** for each $\sigma^{(i)}$.
- Overall, the union of the grids form a uniform pattern, so the cost of the static algorithm is **log n** (for constant degree).

Further Reading

PERFORMANCE 2020, arXiv 2020, APOCS 2021

Online Dynamic B-Matching

With Applications to Reconfigurable Datacenter Networks

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ABSTRACT

This paper initiates the study of online algorithms for the maximum weight b -matching problem, a generalization of maximum weight matching where each node has at most $b \geq 1$ adjacent matching edges. The problem is motivated by emerging optical technologies which allow to enhance datacenter networks with reconfigurable matchings, providing direct connectivity between frequently communicating racks. These additional links may improve network performance.

An emerging intriguing alternative to these static datacenter networks are reconfigurable networks [11, 13, 26, 31, 32, 40, 43, 50, 51, 64, 65, 68]: networks whose topology can be changed *dynamically*. In particular, novel optical technologies allow to provide “short cuts”, i.e., direct connectivity between top-of-rack switches, based on dynamic matchings. First empirical studies demonstrate the potential of such reconfigurable networks, which can deliver very high bandwidth efficiency at low cost.
The matchings provided by reconfigurable networks are

Scheduling Opportunistic Links in Two-Tiered Reconfigurable Datacenters

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Abstract—Reconfigurable optical topologies are emerging as a promising technology to improve the efficiency of datacenter networks. This paper considers the problem of scheduling opportunistic links in such reconfigurable datacenters. We study the online setting and aim to minimize flow completion times. The problem is a two-tier generalization of classic switch scheduling problems. We present a stable-matching algorithm which is $2 \cdot (2/\varepsilon + 1)$ -competitive against an optimal offline algorithm, in a resource augmentation model: the online algorithm runs

particular, we consider a two-stage switch scheduling model as it arises in existing datacenter architectures, e.g., based on free-space optics [11]. In a nutshell (a formal model will follow shortly), we consider an architecture where traffic demands (modelled as *packets*) arise between Top-of-Rack (ToR) switches, while opportunistic links are between lasers and photodetectors, and where many laser-photodetector combinations can serve traffic between a pair of ToRs. The goal is

ReNets: Statically-Optimal Demand-Aware Networks*

Chen Avin[†] Stefan Schmid[‡]

Abstract

This paper studies the design of *self-adjusting* datacenter networks whose physical topology dynamically adapts to the workload, in an *online* and *demand-aware* manner. We propose *ReNet*, a self-adjusting network which does not require any predictions about future demands and amortizes reconfigurations: it performs as good as a hypothetical static algorithm with perfect knowledge of the future demand. In particular, we show that for arbitrary *sparse* communication demands, *ReNets* achieve *static optimality*, a fundamental property of learning algorithms, and that route lengths in *ReNets* are proportional to existing lower bounds, which are known to relate to an *entropy* metric of the demand. *ReNets* provide additional desirable properties such as *compact* and *local* routing and flat addressing, therefore ensuring scalability and further reducing the overhead of reconfiguration. To achieve these properties, *ReNets* combine

we consider the design of DANs which provide short average route lengths by accounting for locality in the demand and by locating frequently communicating node pairs (e.g., a pair of top-of-the-rack switches) topologically closer. Shorter routes can improve network performance (e.g., latency) and reduce costs (e.g., load, energy consumption) [6].

DANs come in two flavors: *fixed* and *self-adjusting*. Fixed DANs can exploit *spatial* locality in the demand. It has recently been shown that a fixed DAN can provide average route lengths in the order of the (conditional) *entropy* of the demand [7, 8, 9], which can be, for specific demands, much lower than the $O(\log n)$ route lengths provided by demand-*oblivious* networks. However, fixed DANs require *a priori* knowledge of the demand.

On the contrary, *self-adjusting* DANs do not require such knowledge and can additionally exploit *temporal* locality by adapting the topology to the demand in

Future Work: Models, Metrics, Algos



Notion of self-adjusting networks opens a **large uncharted field** with many questions:

- Metrics and algorithms: by how much can load be lowered, **energy** reduced, quality-of-service improved, etc. in demand-aware networks? Even for **route length** not clear!
- How to **model** reconfiguration costs?
- Impact on **other layers**?

Requires knowledge in networking, distributed systems, algorithms, performance evaluation.

Conclusion

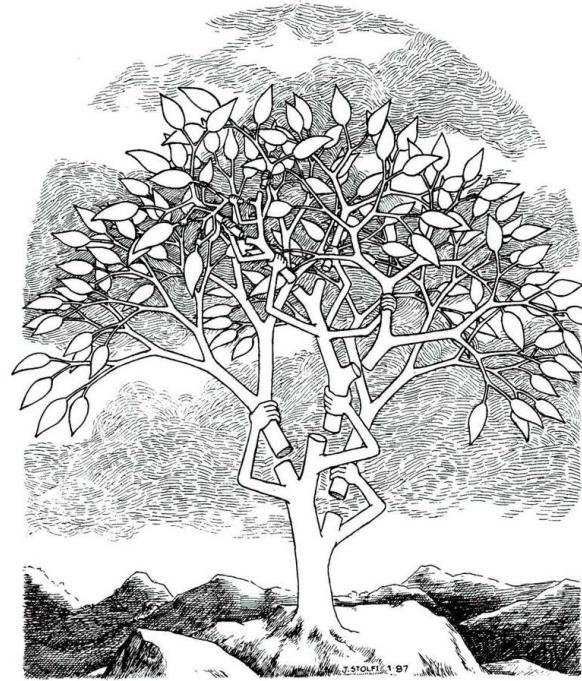
→ Demand-aware networks

- Much potential...
- ... if demand has structure
- Metrics? E.g., entropy

→ Avenues for future work

- Dense communication
- Dynamic optimality
- Distributed control plane

Thank you!

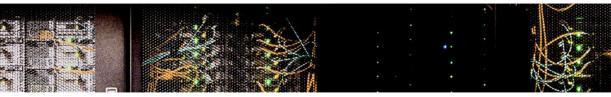


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Websites

SELF-ADJUSTING NETWORKS
RESEARCH ON SELF-ADJUSTING DEMAND-AWARE NETWORKS

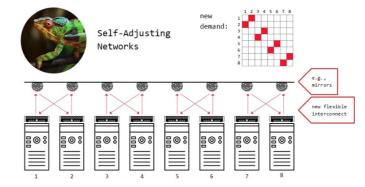
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AdjustNet

Breaking new ground with demand-aware self-adjusting networks

Our Vision:
Flexible and Demand-Aware Topologies



MARCH 17, 2020

This site provides an overview of our ongoing research on the foundations of self-adjusting networks.

WEBSITE LAUNCHED!

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Project website

TRACE COLLECTION
WAN AND DC NETWORK TRACES

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The following table lists the traces used in the publication: **On the Complexity of Traffic Traces and Implications**
To reference this website, please use: `bibtex`

File Name	Source Information	Type	Lines	Size	Download
exact_BoxLib_MultiGrid_C_Large_1024.csv	High Performance Computing Traces	Traces	17 947 800	151.3 MB	Download
exact_BoxLib_CNS_NoSpec_Large_1024.csv	High Performance Computing Traces	Traces	1 108 068	9.8 MB	Download
cesar_Nekbone_1024.csv	High Performance Computing Traces	Traces	21 745 229	184.0 MB	Download

<https://trace-collection.net/>
Trace collection website

Further Reading

Static DAN

Demand-Aware Network Designs of Bounded Degree

Chen Avin Kaushik Mondal Stefan Schmid

Abstract Traditionally, networks such as datacenter interconnects are designed to optimize worst-case performance under *arbitrary* traffic patterns. Such network designs can however fail from optimal when considering the *actual* workloads and traffic patterns which they serve. This observation led to the development of demand-aware datacenter interconnects which can be reconfigured depending on the workload.

Motivated by these trends, this paper initiates the algorithmic study of demand-aware networks (DANs), and in particular the design of bounded-degree networks. The inputs to the network design problem are a discrete communication request distribution, \mathcal{D} , define all communicating pairs from the nodes set V , and a bound, Δ , on the maximum degree. In turn, our objective is to design an (undirected) demand-aware network $N = (V, E)$ of bounded-degree, Δ , which provides short paths between frequently communicating nodes distributed across N . In particular, the designed network should minimize the *expected path length* on N (with respect to \mathcal{D}), which is a basic measure of the

1 Introduction

The problem studied in this paper is motivated by the advent of more flexible datacenter interconnects, such as ProjecToR [29, 31]. These networks aim to overcome the inherent shortcomings of traditional datacenter network designs: the fact that network designers must decide *in advance* on how much capacity to provision between electrical packet switches, e.g., between Top-of-Rack (ToR) switches in datacenters. This leads to an undesirable tradeoff [32]: either capacity is over-provisioned and therefore the interconnect expensive (e.g., a fat-tree provides full-bisection bandwidth), or one may risk congesting traffic in a poor cloud application placement. Accordingly, we initiate the ProjecToR study of demand-aware datacenter interconnects, allowing to establish links flexibly and in a *demand-aware* manner. For example, direct links or at least short communication paths can be established between frequently communicating ToR switches. Such links can be implemented using a bounded number of lasers, mirrors,

Robust DAN

rDAN: Toward Robust Demand-Aware Network Designs

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Abstract

We currently witness the emergence of interesting new network topologies optimized towards the traffic matrices they serve, such as demand-aware datacenter interconnects (e.g., ProjecToR) and demand-aware peer-to-peer overlay networks (e.g., SplayNets). This paper introduces a formal framework and approach to reason about and design robust demand-aware networks (DAN). In particular, we establish a connection between the communication frequency of two nodes and the path length between them in the network, and show that this relationship depends on the *entropy* of the communication matrix. Our main contribution is a novel robust, yet sparse, family of networks, short rDANs, which guarantees an expected path length that is proportional to the entropy of the communication patterns.

Overview: Models

Toward Demand-Aware Networking: A Theory for Self-Adjusting Networks

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 The authors take full responsibility for this article's technical content. Comments can be posted through CCR Online.

ABSTRACT

The physical topology is emerging as the next frontier in an ongoing effort to render communication networks more flexible. While first empirical results indicate that these flexibilities can be exploited to reconfigure and optimize the network toward the workload it serves and, e.g., providing the same bandwidth at lower infrastructure cost, only little is known today about the fundamental algorithmic problems underlying the design of reconfigurable networks. This paper initiates the study of the theory of demand-aware, self-adjusting networks. Our main position is that self-adjusting networks should be seen through the lens of self-adjusting datastructures. Accordingly, we present a taxonomy classifying the different algorithmic models of demand-oblivious, fixed demand-aware, and reconfigurable demand-aware networks, introduce a formal model, and identify objectives and evaluation metrics. We also demonstrate by examples the inherent



Figure 1: Taxonomy of topology optimization

design of efficient datacenter networks has received much attention over the last years. The topologies underlying modern datacenter networks range from trees [7, 8] over hypercubes [9, 10] to expander networks [11] and provide high connectivity at low cost [1].

Until now, these networks also have in common that their topology is *fixed* and *oblivious* to the actual demand (i.e.,

Static Optimality

ReNets: Toward Statically Optimal Self-Adjusting Networks

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Abstract

This paper studies the design of *self-adjusting* networks whose topology dynamically adapts to the workload, in an *online* and *demand-aware* manner. This problem is motivated by emerging optical technologies which allow to reconfigure the datacenter topology at runtime. Our main contribution is *ReNet*, a self-adjusting network which maintains a balance between the benefits and costs of reconfigurations. In particular, we show that *ReNets* are *statically optimal* for arbitrary sparse communication demands, i.e., perform at least as good as any fixed demand-aware network designed with a perfect knowledge of the *future* demand. Furthermore, *ReNets* provide *compact* and *local routing*, by leveraging ideas from self-adjusting datastructures.

1 Introduction

Modern datacenter networks rely on efficient network topologies (based on fat-trees [1], hypercubes [2, 3], or expander [4] graphs) to provide a high connectivity at low cost [5]. These datacenter networks have in common that their topology is *fixed* and *oblivious* to the actual demand (i.e., workload or communication pattern) they currently serve. Rather, they are designed for all-to-all communication patterns, by ensuring properties such as full bisection bandwidth or $O(\log n)$ route lengths between *any* node pair in a constant-degree n -node network. However, demand-oblivious networks can be inefficient for more specific demand patterns, as they usually arise in *concurrent* scenarios. Theoretical studies show that two important issues often

Dynamic DAN

SplayNet: Towards Locally Self-Adjusting Networks

Stefan Schmid¹, Chen Avin^{*,}, Christian Scheideler, Michael Borokhovich, Bernhard Haeupler, Zvi Lotker

Abstract—This paper initiates the study of locally self-adjusting networks: networks whose topology adapts dynamically and in a decentralized manner, to the communication pattern σ . Our vision can be seen as a distributed generalization of the skip search tree paradigm proposed by Sleator and Tarjan [22].

In contrast to their splay trees which dynamically optimize the lookup costs from a single *node* (namely the tree root), we seek to minimize the *average* cost between arbitrary communication pairs in the network.

As a first step, we study distributed binary search trees (BSTs), which are often used for storage of growing datasets. We propose a simple model which captures the fundamental tradeoff between the benefits and costs of self-adjusting networks.

We present the *SplayNet* algorithm and formally analyze its performance. We prove its optimality with respect to some metric, namely the average distributed communication costs and networks such as skip graphs [2, 13] have to support *routing requests* between arbitrary pairs (*or peers*) of communicating nodes; in other words, both the source as well as the destination of the requests become variable. Figure 1 illustrates the difference between classic and distributed binary search trees.

In this paper, we ask: Can we reap similar benefits from self-adjusting *entire networks*, by arguably reducing the distance between source and destination nodes?

As a first step, we explore fully decentralized and self-adjusting Binary Search Tree networks: in these networks, nodes are arranged in a binary tree which respects node identifiers. A BST topology is attractive as it supports greedy routing: a node can decide locally to which port to forward a request given its destination address.

1 INTRODUCTION

In the 1980s, Sleator and Tarjan [22] proposed an appealing new paradigm to design efficient Binary Search Tree (BST) datastructures: rather than optimizing traditional metrics such

Concurrent DANs

CBNet: Minimizing Adjustments in Concurrent Demand-Aware Tree Networks

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Abstract—This paper studies the design of demand-aware network topologies networks that dynamically adapt themselves toward the demand they currently serve, in an *online* manner. While demand-aware networks may be significantly more efficient than demand-oblivious ones, they are still costly. Furthermore, a centralized controller of such networks may become a bottleneck.

CBNet is based on concepts from self-adjusting data structures, and in particular, CBTrees [12]. CBNet gradually adapts the network topology toward the communication pattern in an online manner, i.e., without previous knowledge of the demands distribution. At the same time, *bidirectional semi-splaying* and counters are used to maintain state, minimize reconfigurations

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